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FOREST INSECT POPULATION DYNAMICS

Proceedings of the Forest Insect Population Dynamics Workshop, West Haven, Connecticut 23-27 January 1967

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

Foreword

THE PURPOSE of the Forest Insect Population Dynamics Workshop was to permit some probing in depth of forest insect population systems and to provide an opportunity for the exchange of ideas and information in this subject. Organized and developed primarily for Forest Service personnel interested or involved in quantitative population studies of forest insects, the Workshop was augmented by outside scientists especially knowledgeable and experienced in pertinent facets of population dynamics. The program was oriented to the researcher, with emphasis on approaches and methods of analysis, but with due consideration of output and applications.

The format was simple. One day was given to each of four major subject areas. The primary presentations, which comprise the text of this publication (with the exceptions noted below), were given in the mornings, followed by questions, answers, and discussion of the subject.

The presentation of Dr. Wyatt W. Anderson (then with Yale University) on the fundamentals of population genetics and its interplay with population ecology is not included in this Proceedings because of the basic nature of the information and its availability in standard texts. The paper by Dr. Charles L. Remington (Yale University) on the genetic consequences of insect population displacement or transport is omitted also because it has been published in Volume 15 (1968) of the Annual Review of Entomology.

Unfortunately the taped recordings of the open discussions could not be transcribed adequately, and so this vital portion of the Workshop cannot be included.

— WILLIAM E. WATERS

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FOREST INSECT POPULATION DYNAMICS— SOME BASIC CONSIDERATIONS

by WILLIAM E. WATERS, Chief, Forest Insect Research Branch, Forest Service, U. S. Department of Agriculture, Washington, D. C.

THE STUDY of biological population systems — conscientious and concentrated as it may be — requires a certain philosophical buffering of the sort expressed by this whimsey of Omar Khayam.

> Into this Universe, and *Why* not knowing
> Nor *Whence,* like Water willy-nilly flowing;
> And out of it, as Wind along the Waste,
> I know not *Whither,* willy-nilly blowing.

Man probably has always been concerned with changes in the nature and abundance of living things — at least of those things that affect his mode of living and survival. Studies in population dynamics today cover a broad spectrum of taxa, and encompass or merge with many subject matter fields. Most investigations have been — and still are — directed to objects or problem areas that relate to our own welfare: human demography, epidemiology of disease, or the recurrence of pest insects. However, with ample funding, an adequate supply of graduate students and technical assistants, and computer facilities, it is possible at times to investigate population phenomena of little practical consequence but considerable academic or theoretical interest. And, it sometimes seems worthwhile even to probe into the dynamic complexities of purely hypothetical populations.

For good reason, some of the most productive research in population ecology has been conducted in the forest environment. Like the marine environment, which too has been the working ground of some fundamental and meaningful population studies *(Beverton and Holt 1957),* the forest has a continuity in space and time that permits wide-ranging and long-term studies of it as an ecosystem, or of important components within it that may be considered as systems in themselves. Added features are that it

can be traversed thoroughly, and its major constituents can be seen and measured or counted. A corn field or apple orchard has these latter advantages also, but population studies in such environments necessarily are limited in time and place *(LeRoux et al 1963)*.

Our field of interest is, of course, forest insects — insects that feed and reproduce in or on forest trees and cause some injury in the process. Most of our major forest insect pests have been looked at quite intensively at one time or another, but very few have been studied continuously for a long enough period to provide adequate data for really meaningful analysis. Detailed, but truncated records have been obtained on the spruce budworm *(Morris 1963)*, larch sawfly *(Lejeune 1955)*, and gypsy moth *Campbell 1967)* in this country and Canada, and on a very few forest insects elsewhere, such as the larch budmoth in Switzerland *(Auer 1961, Baltensweiler 1967)*.

Now, in developing and carrying out studies of the population dynamics of the gypsy moth in northeastern United States, we have needed to clarify terms and to do a double-take on some of the mathematical models being used or proposed for analytical purposes. And, in moments of real soul-searching we have been compelled to ask just what are we studying here, what are we really after, what is population dynamics anyway?

Let us take a close look at these questions.

Population dynamics, most simply, refers to changes in numbers and, by implication at least, in the qualities of populations of living things.

Then, studies in population dynamics must concern themselves with (1) defining the population in question, (2) measuring the changes in it, and (3) determining the factors causing the changes, or perhaps just associated with them. It is implicit that the population boundaries, the measured changes, and the relations among components be specified, observed, or derived in quantitative terms and that some form of analysis (mathematical or otherwise) be utilized to obtain the desired information.

The most cursory review of the subject will show that the population systems reported on differ in various ways: (1) the

populations range from small and highly discrete, perhaps artificial, segments of a whole population to complete inventories of the whole—the latter is rare, and each case usually is a sample of unknown proportions and representativeness; (2) the objectives of study, as stated for the record, vary in all manner of ways—more often than not they are simply *constraints* or specifications of *limits,* not statements of purpose; (3) the population parameters measured or estimated and the criteria of change are not at all consistent—and they sometimes are not even the proper ones for the stated objective(s); and (4) the methods of analysis, and resultant interpretations, range from oversimplification to incomprehensible complexity.

Within the sphere of forest insects specifically our objectives may be to obtain:

- Insight into the system *per se.*
- Predictors or predictive equations of natural population trends (both short- and long-term).
- Basic information for judging when, where, and how the insect population(s) can be suppressed or regulated by silvicultural practices, biotic and chemical control, or other means.
- Some means of predicting long-term outcomes of the foregoing control or regulatory methods—applied singly or in combination—and corollary bases for developing optimal strategy for integrated control programs.
- Other, less well defined purposes.

As to general approach, we may proceed in either of two directions:

Particular → *Whole or General*

This is the traditional approach in forest insect ecology, and in animal ecology in general—exemplified by studies of parasitism and predation, dispersal, fecundity, weather and climate effects, and so forth.

Whole → *Particular*

Biological systems traditionally are viewed as hopelessly complex —except by the population geneticists perhaps—but biologists now are drawing on the optimism and experience in econometrics

and physical systems analysis to attempt this approach—for example, the use of life tables and pertinent multivariate analysis in an orderly sequence *(Morris 1963, Morris 1965, Campbell 1967)*.

The objectives cited above may overlap somewhat, so that a study directed to one may provide information relevant to another objective. But it is not possible to be equally successful in regard to *all* objectives. Similarly, whichever approach is taken for whatever objective, model building to maximize realism, generality, and precision may achieve a fair measure of two but not all three of these qualities in any instance. Thus, models of biological populations may be characterized generally as *(Levins 1966)*:

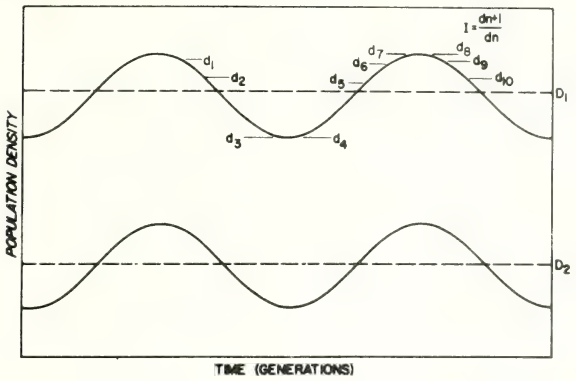
1. High in realism and precision, low in generality.
2. High in generality and precision, not very realistic.
3. High in realism and generality, low in precision.

Strategy in model-building then should be knowledgeable and purposeful, not simply inadvertent, with respect to the particular population system involved and the prime objective of study.

What about the population parameters of interest, the criteria of change, and the bases for evaluating significance or importance of related factors (considered as constants or variables)?

First of all, the data may be in a form unsuitable for analysis. Is a transformation needed—either to fulfill the minimal requirements of a particular analysis (analysis of variance, say) or simply to allow the data to be incorporated into a particular model (for example, transformation to logarithms to convert a multiplicative model into additive form)? Do we need an estimate of the spatial or temporal distribution parameter(s); or are the mean, variance, and derived statistics sufficient? Is sampling error present? Can we estimate it? And if so, how is it entered into the analysis? And what values are to be used for mortality and survival in life tables and in subsequent analyses of them—*apparent* (based on the number of individuals alive at the beginning of an age interval) or *real* (based on the number alive at the beginning of the generation)? To my knowledge, no analyses of life tables of forest insects have been made as yet using *real*

Figure 1.—Schematic representation of oscillations in numbers of two forest insect populations.



mortalities (and survival rates). Different interpretations and/or conclusions as to the "critical" factors might arise from the use of these *real* values as compared with analytical results based on the *apparent* values.

Then, what is the dependent variable? We may be concerned with changes in *absolute (or relative) density* or with changes in *trend in density.* Both are important, of course, in the dynamics of any population system. Both have been given as the dependent variable in recently published theoretical and empirical population models *(Watt 1961, Morris 1963, Campbell 1967).*

Further, in the probing of relationships we find that we may be analyzing the relations of *mean values* (when regression coefficients are taken as the measure of relationship) or the relations of the *variances* of the dependent and independent variables (when r^2, the coefficient of determination, is used). A difference in concept and interpretation is involved here. When *variability* is the criterion, it becomes axiomatic that any factor having a more or less constant effect over time is not important. And if attention is focused (analytically speaking) on rate of change in numbers rather than density, we may indeed be restricting interpretations. Are we not interested in factors that fix or alter mean density levels, and does it matter whether they act as constants or variables in so doing?

A look at Figure 1 may clarify some of these points.

This is a schematic diagram of changes in density of two forest insect populations, differing obviously in their mean density levels, designated by the two horizontal dashed lines D_1 and D_2. The points on the upper population curve, marked d_1, d_2, ... d_{10}, indicate density at particular times. As indicated, the index of population trend, I, is simply the ratio of two successive densities.

Now, the density level of a particular population may be the same at different times—for example d_1, d_6, and d_9—and the rate of change too may be about the same at different times in the same cycle or in different cycles—for example,

$$\frac{d_2}{d_1} \text{ and } \frac{d_{10}}{d_9}, \quad \frac{d_4}{d_3} \text{ and } \frac{d_8}{d_7}.$$

Moreover, the latter, I values may be identical in two separate populations that differ significantly in mean density level.

The whole population system of any forest insect (or other animal, for that matter) will encompass a spectrum of such point densities and I values, and the models developed thus far to analyze life table data do not distinguish between the values in different subpopulations. All are pooled, and thus relationships may be confounded. Segregation or stratification of life tables by mean density level categories, at least, is needed to resolve this difficulty. More refined stratification should further reduce confounding of time-place effects. Campbell's analysis of gypsy moth life table data has demonstrated the importance of this *(Campbell 1967)*.

A more general point can be made from this diagram. Long-term oscillations in population numbers are characterized fully by three basic parameters: (1) mean density level, (2) amplitude, and (3) periodicity. The form(s) of curves for forest insect pests will differ with respect to one or more of these parameters. It is evident that control or regulation can be directed to, or involve, one or all of them. If population regulation is an objective, then we should use all knowledge gained of each insect population system to decide on which pathway to follow—lowering the mean density level, reducing amplitude of the

oscillations, extending the period between peaks of abundance, or any combination of these—and how best to achieve it.

It probably is fitting to close this very incomplete resumé of some basic considerations in the study of forest insect population dynamics with another verse of Omar, the Wise.

> Myself when young did eagerly frequent
> Doctor and Saint, and heard great argument
> About it and about : but evermore
> Came out by the same door where in I went.

Literature Cited

Auer, C.
1961. Ergebnisse zwölfjähriger quantitativer Untersuchungen der Populations Bewegung des Grauen Lärchenwicklers *Zeiraphera griseana* Hübner (=*diniana* guénée) im oberengadin (1949/60). Schweiz. Anst. f. Forstl. Versuchsw. Mitt. 37:175-263.

Baltensweiler, W.
1967. The cyclic population dynamics of the grey larch tortrix, Zeiraphera griseana Hübner (=*semasia diniana* guénée) (lepidoptera: tortricidae). 88-97. Insect Abundance, Symp. Royal Ent. Soc. London: Blackwell Sci. Pub. 4. Oxford and Edinburgh.

Beverton, R. J. H., and S. J. Holt.
1957. On the dynamics of exploited fish populations. 533 pp. H. M. Stationery Office, London.

Campbell, R. W.
1967. The analysis of numerical change in gypsy moth populations. Forest Sci. Monogr. 15, 33 pp.

LeJeune, R. R.
1955. Population ecology of the larch sawfly. Canad. Entomol. 87:111-117.

LeRoux, E. J., R. O. Paradis, and M. Hudon.
1963. Major mortality factors in the population dynamics of the eye-spotted bud moth, the pistol casebearer, the fruit-tree leaf roller, and the european corn borer in Quebec. Entomol. Soc. Canada Mem. 32, pp. 67-82.

Levins, Richard.
1966. The strategy of model building in population biology. Amer. Sci. 54:421-431.

Morris, R. F. ed.
1963. The dynamics of epidemic spruce budworm populations. Entomol. Soc. Canada Mem. 31, 332 pp.

Morris, R. F.
1965. Contemporaneous mortality factors in population dynamics. Canad. Entomol. 97:1173-1184.

Watt, K. E. F.
1961. Mathematical models for use in insect pest control. Canad. Entomol. 93, Suppl. 19, 62 pp.

APPROACHES TO THE STUDY OF POPULATION DYNAMICS

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THERE ARE MANY approaches to the study of population dynamics. On one scale, they range from the study of a single life system to the study of the whole ecosystem—that is, from the study of a single animal species and only those environmental variables that affect its numbers significantly, to the study of community structure, energetics, or productivity. On another scale, they may be concerned primarily with the proximate causes of year-to-year changes in population density—or primarily with the ultimate, or evolutionary, explanation for the persistence or relative abundance of a species. Most of us whose interest in population dynamics stems from forest entomology tend to work with individual life systems and to develop models based on the proximate variables, and my remarks will be concerned with this aspect of population work.

Several approaches to the development of proximate models for single species have been tested but, in my opinion, no really adequate model has yet been produced. In fact, our work in this field is in such an early stage of development that I don't believe we can even say which approach offers the most promise. One object of our work on forest insects at Fredericton is to test different approaches, and I shall first attempt a brief appraisal of three types of models that have been produced, and then describe some preliminary results obtained from the integrated use of two approaches.

Life-Table Approach

Table 1 presents an example of age-specific models produced by the development of life tables for natural populations *(Morris et al 1963)*. Survival (S) is simply population density at the end

Table 1.—Age-interval survival models for the spruce budworm, based on life-table studies

Age-interval survival[1]	Model	Proportion of variation explained
S_E	None	—
S_S	$0.448 - 0.0245\ F_d + \frac{1.1123}{N_S} - 0.0533 \log D_{cc}$	0.49
S_L	$[S_{par}]\ [.096 + N_L e^{-(4.87 + .009N_L)}]\ [1.5797\text{-}0.0396Z]$ $[-3.85 + 6.30\ T/H - 1.97\ T^2/H^2]\ [.67 + 0.009\ F_i]$	.56
S_P	$2.488 - \frac{120.35}{T_{max}}$	.60
2P ♀	$0.879 - \frac{28.52}{T_{mP}}$	.44
P_F	$100.72 - 0.16\ N_L + \frac{89.35}{D_y}$	.85
S_A	None	—
S_G	Combined age-interval models	.41

[1] Legend:

D_{cc} = Cumulative defoliation, obtained by adding values for defoliation of current year's shoots over successive years.
D_y = Defoliation history of a stand, expressed as the number of successive years in which loss of current foliage was practically 100%.
F_d = Average diameter of the host trees in a stand.
F_i = Forest isolation index.
H = Humidity index for a specified period.
N_L = Number of large larvae (third instar).
N_S = Number of small larvae (first instar) per 10 square feet of foliage.
P_F = The proportion of F that can be achieved by the females of a given population, as revealed by reductions in female size associated with suboptimal feeding conditions during the larval period.
P ♀ = The proportion of adults that are females.
S_A = Survival of adults up to and including the time of oviposition.
S_E = Survival of eggs to eclosion = N_S/N_E.
S_G = Survival in any generation.
S_L = Survival of larger larvae (i.e., instars 3, 4, 5, 6) = N_P/N_L.
S_P = Survival of pupae = N_A/N_P.
S_{par} = Survival from parasites during a specified age interval.
S_S = Survival of small larvae (i.e., instars 1, 2) = N_L/N_S.
T = Temperature index for a specified period of time.
T_{max} = Maximum daily temperature averaged over a specified period of time.
T_mP = Mean daily temperature averaged over the pupal period.
Z = Index of phenological development, based on criteria described each time the symbol is used.

Table 2.—"Key-factor" models for the prediction of density in year t+1 from density and other variables measured in year t

Species	Model[1]	Proportion of variation explained
Spruce budworm *(Morris et al 1963)*	$\log N_{t+1} = 1.37 + .68 \log N_t S_{par} S_{pred} + .14 (T_{max} - 66.2°)$	0.79
Black-headed budworm *(Miller 1966)*	$\ln N_{t+1} = .714 + .86 \ln N_t S_{par} + .004 (Heat - 1169°)$	.92
European spruce sawfly: *(Neilson & Morris 1964)*		
Gen 1: Gen 2, same year	$\log N_{t+1} = .65 + .89 \log N_t S_{par} S_{dis} + .12 (R - 6.73'')$	.85
Gen 2: Gen 1, next year	$\log N_{t+1} = 1.04 + .64 \log N_t S_{par} S_{dis}$	.60

[1] Legend:

N_t = Number of insects in a given stage in any year t.
N_{t+1} = Number of insects in the same stage in year t+1.
S_{par} = Survival from parasites during a specified age interval; i.e., 1—proportion killed by parasites.
S_{pred} = Survival from predators during a specified age interval; i.e., 1—proportion killed by predators.
S_{dis} = Survival from disease during a specified interval; i.e., 1—proportion dying due to disease.
T_{max} = Maximum daily temperature averaged over a specified period of time.
Heat = Degree-days measured as daily mean temperatures less 42° F. accumulated for the period June 1 - August 20.
R = Number of inches of rainfall in any year.

of an age-interval divided by that at the beginning, and the dependent variables in the left-hand column refer to the survival of eggs, small larvae, large larvae, pupae, the sex ratio and fecundity, the survival of adults and, finally, the survival of the whole generation. I don't propose to discuss these models in any detail but only to refresh your memory as to their general form.

Characteristic of this approach is a rather massive, and almost continuous, sampling program designed to provide estimates of population density for as many stages as possible in the life history of the insect. The independent variables are generally selected in two ways. First, historical information on the past behavior of the population, including the pattern of damage, suggests certain hypotheses as to the factors affecting density. Then a fishing expedition is conducted, using the regression techniques on which the model is based, to see whether additional variables can be found that appear to have a significant effect on survival.

"Key-Factor" Approach

Table 2 shows examples of a simpler type of model, based on what I call, for want of a better name, the "key-factor" approach *(Morris 1959, 1963)*. Only one population fix is obtained during each generation, based on the developmental stage of the insect that best lends itself to sampling. Then regression methods are used to obtain the best predictive equation for population density in the next generation (N_{t+1}) from population density (N_t) and other key variables in the present generation. Actually, this approach is similar to the life-table approach. The independent variables are selected in the same way and the main point of difference is that, as a result of the reduced frequency of sampling, age-specific sub-models are not possible. Some workers, such as Varley and Gradwell *(1960)* use methods that are intermediate between the two.

"Process" Approach

Table 3 presents some models based on what I call, again for want of a better term, "process" studies. Here the investigator, instead of concerning himself with the whole life system, has

Table 3.—Examples of some different types of "process" models to explain the number of insects attacked by parasites or predators

(1). Deductive (Nicholson and Bailey)

$$N_A = N\,(1 - e^{\frac{-a'P}{N}})$$

(2). Deductive – inductive (Watt)

$$N_A = PK(1 - e^{-aNP^{1-b}})$$

(3). Components analysis (Holling)

(Summary of fragmental equations)

Hunger:

$$H = HK(1 - e^{-AD(TF)})$$

or

$$H = HK + (HO - HK)e^{-AD(T)}$$

Shape of the reactive field:

$$r_a = r_o/(1 + C\theta^2)$$

Area of reactive field:

$$A = KA(GM(H - HT))^2, \qquad H > HT$$
$$A = O, \qquad H \leqq HT$$

Speed of movement of mantid:

$$VD = O$$

Speed of movement of prey:

$$VY = (V_{max} - V_{min})\,e - a_v N_o + V_{min}$$

Capture success:

$$SC = (SR)(SS)\,e^{-m(TP)}$$

Time spent pursuing prey:

$$TP = (KR(GM)(H - HT) - DS)/VP, \qquad H > HTP$$
$$TP = O, \qquad H \leqq HTP$$

Time spent eating each prey:

$$TE = KE(WE)$$

CONTINUED

Table 3.—Examples of some different types of "process" models to explain the number of insects attacked by parasites or predators (Continued)

Time spent in a "digestive" pause:

$$TD = \frac{1}{AD} \ln \frac{HK - HO}{HK - HT}, \quad H < HT$$

$$TD = O, \qquad H \geqq HT$$

Legend:

For Models (1) and (2)

N_A = Number of prey attacked.
N = Initial number of hosts or prey vulnerable to attack.
P = Number of parasites or predators actually searching.
K = Maximum number of attacks that can be made per P during the period the N are vulnerable.
a,a',b = Constants.

For the Fragmental Equations of (3)

A = Area of reactive field of predator.
AD = Rate of food disappearance or rate of digestion.
a = Rate of successful search.
C = A constant relating to functional operation of compound eye.
θ = Angle of prey to body axis of predator.
DS = Strike distance.
GM = Constant relating distance of perception to hunger.
H = Hunger, as measured by the weight of food required to satiate the predator.
HK = Maximum capacity of gut.
HO = Hunger level after prey is consumed.
HT = Hunger level at which searching for prey begins.
HTP = Hunger level at which pursuit begins.
KA = Areal constant relating area of the predator's field of reaction to the distance of reaction at $\beta = 0°$.
KE = Feeding rate (time per unit weight of food eaten).
KR = Equals KA/π.
m = Constant relating success of pursuit to duration of pursuit.
N_o = Prey density.
r_a = Maximum distance of awareness of prey by predator.
r_o = Maximum distance of reaction to prey directly in front of predator.
SC = Success the predator has in capturing prey that enter its perceptual field.
SR = Recognition success of the success of recognizing a prey that enters the predator's perceptual field.
SS = Strike success or the success of capturing a prey once a strike is made.
T = Time.
TD = Time taken in a digestive pause after a prey is eaten.
TE = Time spent eating each day.
TF = Time of food deprivation timed from a condition of complete satiation.
TP = Time spent in pursuing each prey.

CONTINUED

Table 3.—Examples of some different types of "process" models to explain the number of insects attacked by parasites or predators (Continued)

V_{max} = Maximum velocity of prey at $N_o = 0$.
V_{min} = Minimum velocity of prey at $N_o = \infty$.
VD = Average velocity of predator during searching.
VP = Average velocity of predator during pursuit.
VY = Average velocity of prey during pursuit.
WE = Weight of each prey eaten.

concentrated on a population process with the object of explaining the mode of action of a certain mortality factor. Most of the early models, such as the one proposed by Nicholson and Bailey *(1935)* were purely deductive and do not provide good fits to actual field data. The deductive-inductive model of Watt *(1959)* was derived with good field data in hand, so that different deductive ideas about the mode of action of parasites could be tested for goodness of fit. This model provides an excellent description of the rate of attack of certain spruce budworm parasites, but goodness of fit, by itself, does not necessarily mean that the model provides a correct explanation of the process. In the very detailed components analysis used by Holling *(1966)* the process is broken down into its basic components, and theory and experiment are used hand in hand in order to derive a detailed description and explanation of the process.

It is a curious fact that process studies to date have been mainly confined to parasitism, predation, and competition. When we look for similar studies on physical factors affecting insects we find that some very useful work on behavior and development rates has been done, but few attempts have been made to explore the causal pathways through which these factors affect survival rates or population quality.

Apprasial of Approaches

Now I should like to make a brief appraisal of these approaches, with particular regard to the models in tables 1 and 2:

(1) The models are empirical and purely descriptive, not ex-

planatory. To use only one example, the model for the survival of small larvae (S_s) in table 1 contains F_d (average tree diameter) as one of the independent variables. It does so only because F_d explained more of the variation in survival than did the other stand factors that were measured. It was recognized, however, that mean diameter was related to the amount of foliage per acre, the production of staminate flowers on balsam fir, the number of trees per acre, and the exposure and microclimate of individual crowns. If the causal mechanisms through which stand factors affect survival were known, it should be possible to measure the appropriate variables and to refine this preliminary model to one that would have more biological meaning.

(2) Although sampling error was appreciable, most of the variation in survival not explained by the spruce budworm model could be attributed to failure to measure all the relevant independent variables, or failure to measure them in the best way. This comment, like the first, is related to the methods used for selecting and measuring the independent variables.

(3) My third comment is also related to the first. Interactions among the independent variables are mainly ignored in the model. Since causal pathways were not adequately understood, it was difficult to make reasonable assumptions about modes of interactions.

(4) Most models developed to date suggest that one, or perhaps two, age intervals are critical, and that a few key variables operating in these periods account for most of the variation in generation survival or rate of population change. Thus, although there are many advantages in having models for all age intervals when this is possible, models of the key-factor type might be adequate for many purposes if we had better information of the process type.

(5) The models developed to date for any one species apply to rather limited areas or forest types. Simultaneous population studies over areas where climate and vegetation are very different should lead to models that are more complete, and

also more useful for examining the possibilities of control through environmental manipulation. That is, models should explain population differences associated with place, as well as with time.

(6) Finally, with a few exceptions, most models suggest that there has been very little liaison between population workers in the field and process workers in the laboratory.

It is very easy to be critical, of course, with the omniscience of hindsight, and it is not my intention to disparage the models that have been presented so far by various workers. They represent a very great advance over the qualitative and purely verbal descriptions of life systems that preceded them. I am only interested in considering ways in which they might now be improved.

Approach to Studies on *Hyphantria cunea*

It seems clear that considerable improvement would be possible if field sampling and experimental process studies were to proceed hand in hand as integral parts of the same investigation. The field work would show the relative importance of different key variables that require detailed study, and provide the final test of the predictive powers of the model; while the process work would establish cause and effect, show the best way to measure the independent variables in the field and to model their effects in the analysis, and probably suggest additional variables that should be measured.

The fall webworm, *Hyphantria cunea* Drury, is a good test animal for an integrated approach of this sort. The nests are large and conspicuous at the peak occurrence of the fifth instar, and in New Brunswick and Nova Scotia, where there is only one generation a year, an annual census can be conducted rapidly over large and diverse areas. This leaves most of the year free for process work. Colonies can be established in different situations and at different densities in the field for detailed observations, or reared in the laboratory where such factors as temperature, humidity, and food quality can be controlled in any combination—including combinations that place considerable stress on the popu-

lation. This permits the development of laboratory life tables showing the immediate effect of any stress on a particular stage, as well as the delayed effects on later stages or on later generations.

Some Effects of Heat on *Hyphantria cunea*

The population density of the webworm at any time or place is determined largely by the joint action of five factors, and of these the effects of heat on survival are the most important and also the most complex. To illustrate the type of information provided by the integrated approach, I am now going to list some of the pathways through which heat affects webworm survival. I am using *heat* as a convenient term for the number of degree-days above the webworm's developmental threshold of 51°F., and you should bear in mind that my objective is to develop and test models that will predict—and explain—changes in the population of nests in any area from year to year (that is, from any year, t, to the next year, t+1).

(1) *The rate at which heat is accumulated in any year, t, has direct effects on survival in t and fecundity in t+1.* Heat is accumulated rapidly at high temperatures and slowly at low temperatures, and departures from the webworm's optimum of about 80°F. reduce larval survival, pupal size, and adult fecundity. These relationships, as well as the interaction between heat and humidity, have been derived from life-table studies at both constant and variable temperatures and need not be discussed further at this point.

(2) *The amount of heat in t has direct effects on survival to the census period in t.* Figure 1 shows the occurrence of adults, fifth-instar larvae, and pupae in the field in relation to heat accumulation in a warm year, and figure 2 shows contrasting values for a very cold year. The webworm overwinters as a diapausing pupa in the ground and the moths emerge in June and July. The nest census is conducted at the peak of the fifth instar. The broken lines, based on known heat requirements, represent mortality due to an insufficient accumulation of heat for development.

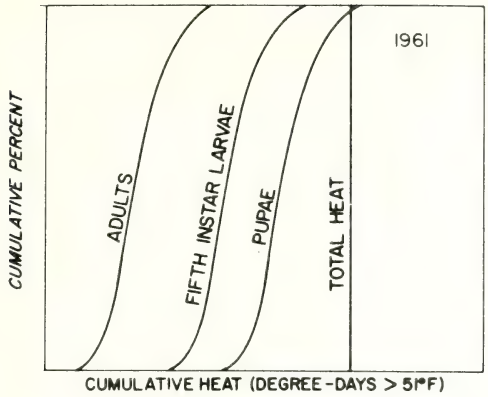

Figure 1.—Occurrence of adults, fifth instar larvae, and pupae of **Hyphantria cunea** in the field in relation to heat accumulation in a warm year.

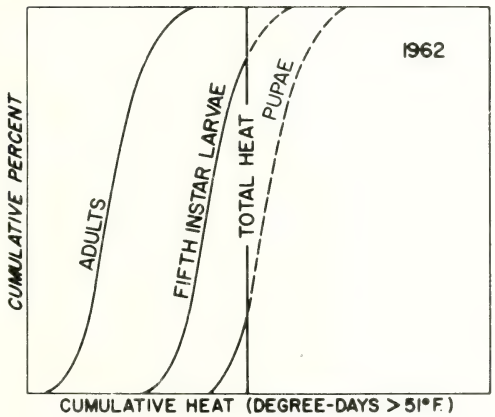

Figure 2.—Occurrence of adults, fifth instar larvae, and pupae of **H. cunea** in the field in relation to heat accumulation in a cold year.

In the cold year, 1962, the progeny of late-emerging adults did not even reach the fifth instar before the end of the developmental season.

(3) *Heat in t has direct effects on survival after the census period in t and hence on the initial population density of t+1.* Figure 1 shows that even in warm years in the Maritime Provinces a small proportion of the population may fail to reach the overwintering pupal stage. In cold years (fig. 2) this proportion becomes very high.

These last two effects of heat are simple and direct, and can be modeled easily, provided the heat requirements of each stage have been carefully determined for both laboratory and field colonies. Their effects on population density can be seen by looking ahead to figure 5, with attention only to the solid lines representing area A. Observe that nest population declined in the cold year, 1962, because some colonies were unable to produce discernible nests; and again sharply in 1963, because many colonies failed to reach the pupal stages in 1962. Note that the scale is logarithmic; the total reduction in population between 1961

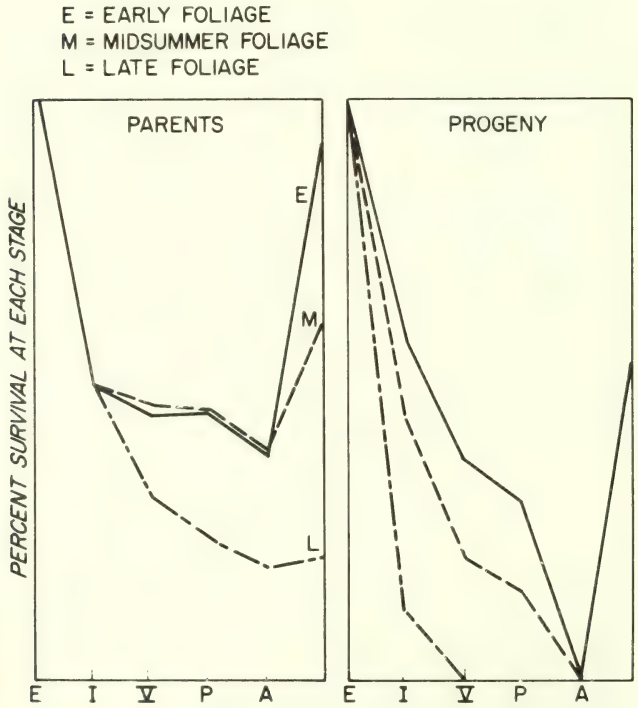

Figure 3.—Survival to successive stages when larvae of the parental generation are reared on early, midsummer, and late foliage collected from the same trees (left side); and survival of progeny of the same three series when the progeny were reared on a deficient synthetic diet (right side). On the bottom scale, E = eggs, I = instar, V = instar, P = pupae, and A = adults.

and 1963 was 99%, largely attributable to lack of heat in 1962.

(4) *Heat in t has indirect effects on survival in t, operating through food quality.* Figure 3, left side, shows the survival to each stage—eggs, I—instar, V—instar, pupae, and adults—when larvae of the same genetic stock are reared under controlled conditions on early (E), mid-summer (M), and late (L) foliage collected from the same trees. The age of foliage usually available to natural populations in the Maritimes varies between M and L, depending on the accumulation of heat. Thus in cold years when feeding has to extend into the late fall, survival is reduced.

(5) *Heat in t has indirect effects on fecundity in t+1, operating through food quality.* This is also shown in the left side of figure 3, where the F represents percentage of possible fecundity. The females of series E produced 600 eggs each, series M about 60% of this, and series L only 20%.

(6) *Heat in t has indirect effects on survival in t+1, operating through a transmitted maternal influence on population quality.* The right side of figure 3 shows the survival of the progeny of the three series on the left, when the progeny were all reared under identical conditions on a deficient synthetic diet. When the parental generation had early foliage, the progeny survived and produced eggs; when it had midsummer foliage, they failed to produce viable adults; and when it had late foliage, the progeny did not reach the fifth instar. When some of the same progeny were reared on foliage in the field, similar results were obtained. That is, maternal food quality had important effects, especially on the viability of the eggs and the survival of the larvae. Thus, when two equally cold years occur in succession, a realistic model should provide for lower survival in the second year because the resistance of the population to additional nutritional stress has been lowered.

(7) *Heat in t has indirect effects on survival in t+1, operating through the influence of nature selection on heat require-*

ments. To explain this, I wish to introduce the term "eclosion heat," which is simply the mean amount of heat required by webworm pupae each spring before the moths will emerge. Each fall larvae are collected from the different census areas, the resulting pupae are overwintered at 35°F, and the progress of moth eclosion is recorded under controlled temperatures the following spring. When it appeared that the heat required for eclosion varied not only from area to area but also from year to year within an area, I suspected at first that it was an artifact associated with collection or rearing methods. However, records for wild adults taken in light traps showed exactly the same trend of variation. Figure 4 is based on light-trap records for a number of years in one area, and it appears that the heat required for eclosion in the spring is determined partly by the total heat of the previous summer. The assumption that this is a result of natural selection is based on the following points:

(a) The required eclosion heat is under genetic control. When like moths are mated, the progeny have the same heat requirements as the parents and when unlike moths are mated, the progeny have heat requirements mid-way between those of the parents.

Figure 4.—The relationship of mean eclosion heat required in any year to the total heat accumulation in the preceding year.

(b) Experimental rearing in environmental chambers is not yet completed, but so far there is no evidence that environmental factors affect the eclosion heat requirements.

(c) Figure 2 shows that there is a very high selection pressure in a cold year against the progeny of the adults that emerge late, and hence against individuals that require the most heat for eclosion. Thus, after a cold year, the mean eclosion heat required by the population is considerably reduced as shown in figure 4. Although the rate of change seems very rapid for a selection process, it should be observed that mating is highly assortative rather than random. That is, since the moths live for only about 8 days, the probability is high that early moths mate with early moths, and late with late.

(d) In a long, warm season, on the other hand, selection should operate against forms that complete development too early. Dispausing pupae lose weight rather rapidly (about 10% per month at 65°F.) before cold weather sets in, and are also exposed to a longer period of severe predation by small mammals. It should be mentioned, however, that figure 4 is based largely on a population that has gone from a warm period to a cold period. The rate at which heat requirements will increase again is not yet known.

(8) *Heat in t—1, t—2, etc. affects population quality in t.* If it is true that there are considerable differences in population quality from year to year and from place to place, arising both from selection and from maternal effects, then presumably quality depends not only on events in the past year but also on events in a number of earlier years. The data have not yet been analyzed to test the significance of such historical effects, but a comparison of the graphs in figure 5 will serve to indicate the possibilities. Area "A" is coastal and has a long developmental season; "B" is inland, the season is always shorter and there are greater deviations

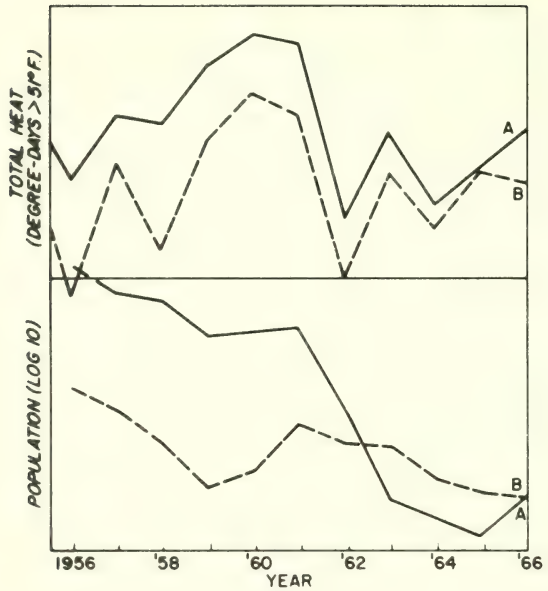

Figure 5.—Total heat accumulation in two study areas, A and B, in the Maritimes from 1956 to 1966 and corresponding population densities in this period.

from the mean, such as those of 1956 and 1958. In both areas, populations increased during the warm years of the early 1950s to a peak in 1956 of about 100 nests per mile in A and 10 nests per mile in B. The cold summer of 1962 was exceptional for A and the population (fig. 5) was reduced by 99%, as described earlier. But population B, which had experienced similar stresses a few years earlier, showed only a moderate reduction. Parasitism and predation in the two areas were not appreciably different during this period. However, heat requirements for eclosion were much higher in A than in B before the population crash, but rather similar afterwards. It is therefore reasonable to suspect that the differential effect of 1962 on the two populations is related to their earlier history. In other words, the longer the population goes without stress, the less prepared it is, qualitatively, when the stress comes along. I have plotted only two areas but similar trends were obtained in five other areas, all leading to the seemingly paradoxical conclusion that the best place to look

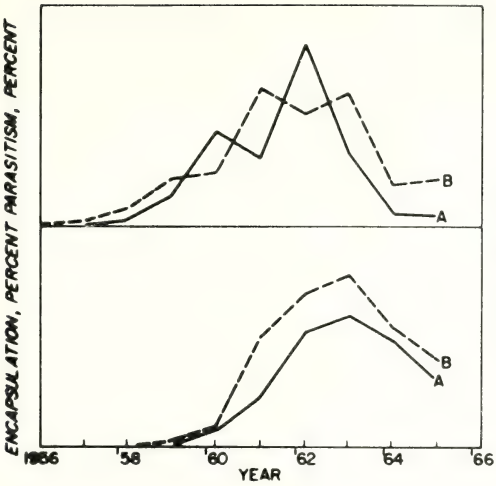

Figure 6. — Percentage parasitism of webworm larvae by **Campoplex validus** in areas A and B from 1956 to 1965 and the percentage encapsulation of **C. validus** eggs over the same period.

for the webworm in times of scarcity, such as 1964-65, is in areas like B where the climate is rigorous, not in favorable areas like A.

(9) *Does heat affect the degree of parasitism?* Figure 6 shows the percent parasitism of webworm larvae by *Campoplex validus* in Areas A and B, and raises some very interesting questions. Where was *Campoplex* during the high webworm populations of the mid-1950's? And why did *Campoplex* increase simultaneously and give about the same level of parasitism in A and B, as well as in the other five areas in the Maritimes, regardless of differences in host density that ranged from less than 1 to nearly 100 nests per mile? This is not the type of interaction that would be expected from a "classical" parasite, or the type that has been demonstrated for some of the effective parasites attacking the European spruce sawfly or black-headed budworm. *Campoplex* has a considerably lower eclosion threshold than *Hyphantria* and we are testing the possibility that its increase over large areas may be related more to synchronization and weather than to host density.

(10) *Does heat affect the degree of encapsulation of Campoplex eggs?* The encapsulation of *Campoplex validus* eggs by

webworm larvae was first observed in 1958, increased to 80% in area B in 1963, and then declined (fig. 6). A very limited number of experiments in cages suggests that large host larvae may encapsulate eggs more readily than small ones, and if this is supported by further work it will show one mechanism through which synchronization, and hence the accumulation of heat above contrasting thresholds, determine the abundance and effectiveness of the parasite.

Appraisal of Approach

In conclusion, ten pathways through which heat may influence the population density and quality of *Hyphantria cunea* have been listed, although some of them are still speculative. The other variables affecting this species will not be discussed, because my object has been only to illustrate the sort of relationships that may be disclosed through a very close integration and cross-fertilization between laboratory process studies and field measurements in areas of diverse climate and vegetation.

It is too early to say whether or not the degree of predictability will be improved through this greater knowledge of causal pathways and processes. A graphical analysis of earlier webworm oscillations in this area suggests that simple empirical models would give some degree of predictability, even if based on such a rough index of heat as mean summer temperature, and even without any knowledge of how heat affects survival. And by the same token, some of the empirical key-factor models of table 2 provide surprisingly good predictability.

It is reasonable to expect, however, that predictability will be improved because the process work has shown how and when heat should be measured. For example, it is clear that we are concerned not only with total heat in year t, but also heat in t+1 up to the census period. We are concerned with heat in a number of past years because of its two effects on population quality. We are concerned with the seasonal distribution of heat. And we are concerned with the accumulation of heat above different thresholds because of the way that this affects synchronization

between the webworm and its food quality, as well as the webworm and its parasites.

In addition to showing how to measure and express the independent variables, the process studies have also suggested limits and forms of functions by means of which their effects on survival may best be modelled. For example, high maximum temperatures in mid-summer can have adverse effects on the webworm, especially when associated with low humidity. For this reason it has been necessary to develop a computer program that will accumulate heat units between different temperature thresholds. Similarly, some insight into the nature of interactions has also been gained.

And most important of all, if the mathematical task of incorporating the different causal pathways into the final model is not too complex, the model should represent a higher level of biological meaning than could be achieved through regression analyses based on field data alone. My hope is that it will be good enough for reliable simulation studies, with the object of learning whether or not density dependence represents an essential aspect of the webworm's system of regulation and what would happen if sequences of warm years extended beyond their normal expectancy. As a result of the effects of natural selection on heat requirements, webworm populations that are increasing during a series of warm years become progressively less able to take advantage of these favorable conditions. It will be instructive to learn how much the genetic parameters in the model, by themselves, contribute to population stability. Finally, it can be shown that population density is related to land use, vegetation types, and other variables which have not been discussed above. It will, therefore, be worthwhile to employ simulation and minimization techniques to see whether cultural manipulation of the environment can be used feasibly to reduce webworm damage.

Note: The results presented above for *Hyphantria cunea* are based on examples drawn from more extensive data and are intended only to illustrate the approach. The more rigorous mathematical analyses that are planned for the whole body of data may alter the form of these freehand trends.

Literature Cited

Holling, C. S.
1966. The functional response of invertebrate predators to prey density. Entomol. Soc. Canada Mem. 48, 86 pp.

Miller, C. A.
1966. The black-headed budworm in eastern Canada. Canad. Entomol. 98: 592-613.

Morris, R. F.
1959. Single-factor analysis in population dynamics. Ecol. 40: 480-588.

Morris, R. F.
1963. Predictive population equations based on key factors. Entomol. Soc. Canada Mem. 32, pp. 16-21.

Morris, R. F., ed.
1963. The dynamics of epidemic spruce budworm populations. Entomol. Soc. Canada Mem. 31, 332 pp.

Neilson, M. M., and R. F. Morris.
1964. The regulation of European spruce sawfly numbers in the Maritime Provinces of Canada from 1937 to 1963. Canad. Entomol. 96: 773-784.

Nicholson, A. J., and V. A. Bailey.
1935. The balance of animal populations I. Proc. Zool. Soc. London 551: 598.

Varley, G. C., and G. R. Gradwell.
1960. Key factors in population studies. J. Anim. Ecol. 29: 399-401.

Watt, K. E. F.
1959. A mathematical model for the effect of densities of attacked and attacking species on the number attacked. Canad. Entomol. 91: 129-144.

STUDIES ON GYPSY MOTH POPULATION DYNAMICS

by ROBERT W. CAMPBELL, Entomologist, Forest Insect and Disease Laboratory, Northeastern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, Hamden, Connecticut.

LIFE TABLES for the gypsy moth were accumulated on 53 generation-years from an area in northeastern New York between 1958 and 1963. Tables 1 and 2 represent typical fates of a cohort from a single egg mass under dense and sparse population conditions.

Table 1.—Life table typical of dense gypsy moth populations in Glenville, N. Y.

x	lx	dxf	dx	100qx
Age interval	Number alive at beginning of x	Factor responsible for dx	Number dying during x	dx as percent of lx
Eggs	250	Parasites	50.0	20
		Other	37.5	15
		Total	87.5	35
Instars I-III	162.5	Dispersion, etc.	113.8	70
Instars IV-VI	48.7	Parasites	2.4	5
		Disease	29.2	60
		Other	12.2	25
		Total	43.8	90
Pre-pupae	4.9	Desiccation, etc.	0.5	10
Pupae	4.4	Parasites	1.1	25
		Disease	0.7	15
		Calosoma larvae	0.9	20
		Other	0.4	10
		Total	3.1	70
Adults	1.3	Sex(S:R = 30:70)	0.9	70
Adult ♀ ♀	0.4	—	—	—
Generation	—	—	249.6	99.84

Table 2.—Life table typical of sparse gypsy moth populations in Glenville, N. Y.

x	lx	dxf	dx	100qx
Age interval	Number alive at beginning of x	Factor responsible for dx	Number dying during x	dx as percent of lx
Eggs	450	Parasites	67.5	15
		Other	67.5	15
		Total	135.0	30
Instars I-III	315	Dispersion, etc.	157.5	50
Instars IV-VI	157.5	Parasites	7.9	5
		Disease	7.9	5
		Other	118.1	75
		Total	133.9	85
Pre-pupae	23.6	Desiccation, etc.	0.7	3
Pupae	22.9	Vertebrate predators	4.6	20
		Other	2.3	10
		Total	6.9	30
Adults	16.0	Sex(S:R=65:35)	5.6	35
Adult ♀♀	10.4	—	—	—
Generation	—	—	439.6	97.69

These life table data were stratified in two ways: first, on the age interval survival rates of female insects only; and, second, by density class. These stratifications preceded our main analyses.

Inferences about the system were drawn from relationships between variation in density and variation in and among its components. Variance components were partitioned by a procedure proposed by Gordon Mott.[1]

Analyses were performed through four levels: first, to identify the age interval survival rates most closely related to changes in population numbers from generation to generation; second, to identify the mortality-causing agents or processes most closely

[1] Mott, D. G. The analysis of determination in population systems. *In* Systems Analysis in Ecology. pp. 179-194. New York: Academic Press Inc. 1966.

related to these survival rates; third, to develop models for these agents or processes; and fourth, to use the foregoing in an attempt to describe or analyze long-range trends.

Some specific results from the first analytical level may clarify the above. The variables used in the generation model are shown in table 3, while the components of variance in density of female eggs at the beginning of a second generation are shown separately for dense and sparse populations in table 4.

The results of these analyses can be summarized:

- Variation in the survival rates of the instar IV - VI female larvae and pupae constituted the greatest sources of variation in density among dense populations. Variation in the survival rate of both instar I - III and IV - VI female larvae was most important among sparse populations.
- Disease was the primary determinant of variation in the survival rate of dense populations of instar IV - VI female larvae, while agents other than disease or parasites were most im-

Table 3.—Variables used in the age-interval model of changes in gypsy moth numbers from one generation to the next

$$\log N_{♀E(n+1)} = \log N_{♀E(n)} + \log S_{♀E} + \log S_{♀r} + \log S_{♀L} + \log S_{♀pp}' + \log S_{♀p}' + \log F♀$$

where:

$N_{♀E(n+1)}$ = Number of female eggs per acre at start of generation (n+1)

$N_{♀E(n)}$ = Number of female eggs per acre at start of generation (n)

$S_{♀E}$ = survival rate of female eggs

$S_{♀r} = (S_{♀s} \cdot S_{♀pp\ (pred)} \cdot S_{♀p\ (pred)} \cdot S_{♀A})$

$S_{♀L}$ = survival rate of large female larvae

$$S_{♀pp'} = \frac{S_{♀pp}}{S_{♀pp\,(pred)}} = \frac{\text{Survival rate of all female prepupae}}{\text{Survival rate of female prepupae from vertebrate predation}}$$

$$S_{♀p'} = \frac{S_{♀p}}{S_{♀pp\,(pred)}} = \frac{\text{Survival rate of all female pupae}}{\text{Survival rate of female pupae from vertebrate predation}}$$

$F_{♀}$ = Number of female eggs deposited per adult female

$S_{♀A}$ = Survival rate of adult females to commencement of egg deposition.

Table 4.—Components of variance in density of females (expressed as percentages of the total variance)

Dense Populations ($N\,♀_{E(n)}$) >50,000, $\sigma^2 = 1{,}251$, $\sigma^2 I\,♀ = 2{,}096$, N = 26

	log $N\,♀_{E(n)}$	log $S\,♀_E$	log $S\,♀_r$	log $S\,♀_L$	log $S\,♀_{pp'}$	log $S\,♀_{p'}$	log $F\,♀$	log $N\,♀_{E(n+1)}$
log $N\,♀_{E(n)}$	18.4	−0.3	−0.7	−22.9	−1.7	−10.7	−6.6	−24.5
log $S\,♀_E$	1.3	−1.6	− 5.4	−0.2	− 0.8	0.5	− 6.5	
log $S\,♀_r$	13.4	1.8	−0.6	− 2.9	−2.4	7.0		
log $S\,♀_L$	87.6	3.3	18.4	5.7	88.5			
log $S\,♀_{pp'}$	0.4	2.0	0.9	4.1				
log $S\,♀_{p'}$	12.3	5.5	23.8					
log $F\,♀$	4.2	7.6						
log $N\,♀_{E(n+1)}$	100.0							

Sparse Populations ($N\,♀_{E(n)}$) <50,000, $\sigma^2 = 0.386$, $\sigma^2 I\,♀ = 0.520$, N = 27

	log $N\,♀_{E(n)}$	log $S\,♀_E$	log $S\,♀_r$	log $S\,♀_L$	log $S\,♀_{pp'}$	log $S\,♀_{p'}$	log $F\,♀$	log $N\,♀_{E(n+1)}$
log $N\,♀_{E(n)}$	122.0	3.6	−61.0	−7.8	−1.5	−4.1	−7.5	43.7
log $S\,♀_E$	3.5	− 6.2	−5.6	−0.4	0.1	0.0	− 5.0	
log $S\,♀_r$	97.5	4.0	0.9	−3.2	0.0	32.0		
log $S\,♀_L$	48.5	0.2	0.0	0.1	39.4			
log $S\,♀pp'$	0.2	0.1	0.3	− 0.1				
log $S\,♀p'$	1.2	0.7	− 5.2					
log $F\,♀$	1.7	− 4.8						
log $N\,♀_{E(n+1)}$	100.0							

portant at this stage among sparse populations. The survival rate of dense populations of the female pupae varied primarily in response to ichneumonids and disease. Variation in the survival rate of the instar I - III larvae was probably primarily a function of variation in the dispersion rate of the newly hatched larvae.

- An index of disease incidence among instar IV - VI larvae was a curvilinear function of insect density, a linear function of precipitation during June, a linear function of the percent of swamp white oak in the overstory, and a function of an interaction between density and precipitation. Several other variables (the apparent survival rate of instar I - III larvae; the proportion of the female pupae killed by ichneumonids; and the number of eggs deposited per adult female) were curvilinear functions of insect density.

- A generation model was developed that describes density at the beginning of a second generation as a function of the environmental variables associated with the above mortality-causing factors. This model was tested against an independent body of data with some success.

This information, with more complete details and interpretive discussion, has now been published.[2]

A study was begun on sparse, stable gypsy moth populations in 1965, and continued in 1966 and 1967. This work began on the assumptions that: (1) variation in the rate of vertebrate predation is mainly determined by the location of the larvae within the environment when the predators are foraging for food; and (2) larval distribution in sparse populations is mainly determined by the distribution and quality of resting places, which the insect uses during daylight. Some of our combined 1965 and 1966 results are summarized in tables 5 and 6. These results support the above assumptions.

An approximate mean value life table is shown for the 1965-66 data (table 7).

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[2] Campbell, R. W. THE ANALYSIS OF NUMERICAL CHANGE IN GYPSY MOTH POPULATIONS. Forest Sci. Monogr. 15, 33 pp. 1967.

Table 5.—Relationship between number of bark flaps per 0.01-acre plot and number of adult gypsy moths produced

Number of bark flaps per plot	Number of plots observed	Total adults	Adults per plot
0	280	6	.02
1	77	4	.05
2 - 3	70	6	.09
4 and over	56	15	.27

Table 6.—Relationship between pupal location, pupal sex, and mortality rate; and between pupal sex and mortality rate from vertebrate predation

Pupal location	Number found		Mortality rate		Mortality from vertebrates	
	♂♂	♀♀	♂♂	♀♀	♂♂	♀♀
Bark flaps	64	27	.78	.85	.20	.41
Other	71	85	.87	.95	.56	.86

Table 7.—Life table typical of sparse gypsy moth populations in northeastern Connecticut

x	lx	dxf	dx	100qx
Age interval	Number alive at beginning of x	Factor responsible for dx	Number dying during x	dx as percent of lx
Eggs	550	Parasites	82.5	15
		Other	82.5	15
		Total	165.0	30
Instars I-III	385	Dispersion, etc.	142.5	37
Instars IV-VI	242.5	Deer mice	48.5	20
		Parasites and Disease	12.1	5
		Other	167.3	69
		Total	227.9	94
Pre-pupae	14.6	Predators, etc.	2.9	20
Pupae	11.7	Vertebrate predators	9.8	84
		Other	0.5	4
		Total	10.3	88
Adults	1.4	Sex(S:R=30:70)	1.0	70
Adult ♀ ♀	0.4	—	—	—
Generation	—	—	549.6	99.93

METHODS OF DEVELOPING LARGE-SCALE SYSTEMS MODELS

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WHEN A MATHEMATICAL model for a complex process is constructed, instead of merely selecting an empirical formula useful for interpolation—as in regression analysis—we try to write one or more differential, difference, or difference-differential equations based on insight into the mechanics of the process under study. Before discussing the methods for building large models, the differences between these three kinds of equations will be explained.

Differential Equations

Differential equations arise whenever a rate of change of some variable with respect to another can be expressed in terms of a continuous set of variate values of one or more other variables. Consider, for example, the simple attack equation *(Watt 1959)* in which

N_A represents numbers attacked,
N_0 represents numbers vulnerable to attack,
P represents the numbers of attackers,
a, b and K are constants, and all numbers have been measured in the same universe,

$$\frac{dN_A}{dN_0} = aP^{1-b}\ (PK\text{-}N_A)$$

This is a differential equation, because the variables P and N_A are assumed to be able to vary continuously. The notion of differential equations can in fact be generalized considerably to include accelerations and higher-order derivatives, squares of derivatives or higher degrees than this, and partial differential equations, in which there are several independent variables, as in

$$\frac{\delta^2 Z}{\delta x^2} + \frac{\delta^2 Z}{\delta y^2} = x^2 + y$$

However, the common element in all differential equations is the notion that the variables can take any value on a continuous scale, including non-integer values. A moment's reflection indicates that such equations do not give an accurate picture in many biological systems, unless we handle them in a special way. Consider an animal laying eggs. It lays 8 eggs, 1 egg, 233 eggs, or 119,236 eggs, but never 6.237 eggs. Consider an area of ground, divided up into squares 10 meters by 10 meters. If there are 9 mice living in one such square, emigration from the square will occur one mouse at a time, not 1.23 mice at a time. Many biological processes have this character, in which variables can take only discrete values. We conclude that difference equations are often more appropriate than differential equations, or at least differential equations must often be treated as difference equations.

Difference Equations

Difference equations are used wherever the variables take only discrete values. For example, the differential equation for exponential growth is

$$\frac{dY}{dt} = rY$$

In contradistinction, the difference equation for exponential growth is

$$\frac{Y_{k+1}-Y_k}{t_{k+1}-t_k} = \frac{\Delta Y}{\Delta t} = rY_k$$

Equation (1) states that at any instant of time, the rate of growth in Y will be proportional to the value of Y at that instant. Equation (2) states that the difference in magnitude of Y from time t_k to time t_{k+1} will be r times the value of Y at t_k. The essential difference is that Y and t are assumed to vary only by discrete (i.e., steplike) values. A book by Goldberg *(1958)* is an excellent introduction to this field for behavioral scientists.

Difference-Differential Equations

Suppose, now, that we wished our dependent variable to be a derivative, as in differential calculus, but our independent variables are to be treated as discrete values at some prior point in

time. Here the exponential growth equation would take the form

$$\frac{dY}{dt} = rY_{t-\tau} \tag{3}$$

where τ is the period of time lag.

No matter what type of equation is most suitable for describing a complex system, the problem faced in all cases is that of determining the particular structure for the model which gives the most realistic description of the system.

In the use of large complex problems with many interaction terms, the most convenient way to approach model construction is by trying to split the problem into bits, so we can deal with the bits individually. For example, suppose we know that Y, the volume of timber grown in a forest per unit time, is a function of 15 other variables, so that we could write

$$Y = f(X_1, X_2 \ldots\ldots\ldots\ldots X_{15}). \tag{4}$$

The first step is to determine how to split (4). Do we have

$$Y = \frac{f(X_1, X_2, X_3)}{f(X_4)} + f(X_5 \ldots\ldots\ldots X_{15}),$$

or $Y = [f(X_1, X_2, X_3,)]\,[f(X_4, X_5, X_6,)]\,[f(X_7 \ldots\ldots\ldots X_{15})]$.

How to combine such component terms, or sub-models, to make a large model will often be apparent from the following two probability theorems.

The addition theorem.—The probability that one out of m events, any two of which are mutually exclusive, occurs is equal to the sum of the probabilities of the occurrence of each event separately.

The multiplication theorem.—The probability that two stochastically independent events occur together is equal to the product of the probabilities of the occurrence of each event separately.

Given that the researcher has determined how to split his problem into pieces, how does he write equations for a sub-model? Suppose that the whole model is

$Y = A \cdot B \cdot C \cdot D$, and the sub-model we are concerned with is

$$A = f(X_1, X_2, X_3). \tag{5}$$

Table 1.—Result from sorting and tabulating data to reveal form of functional relationship

Number of cards in sub-deck	A		X_1		X_2		X_3	
	Total	Mean	Total	Mean	Total	Mean	Total	Mean
5	—	—	—	2	—	2	—	40
5	—	—	—	2	—	2	—	80
5	—	—	—	2	—	2	—	120
5	—	—	—	2	—	4	—	40
5	—	—	—	2	—	4	—	80
5	—	—	—	2	—	4	—	120
5	—	—	—	2	—	8	—	40
—	—	—	—	2	—	8	—	80
—	—	—	—	2	—	8	—	120
						and so on		

To determine the particular form of (5), the analyst can sort the data, using cards, to separate out the effects of X_1, X_2, X_3, by

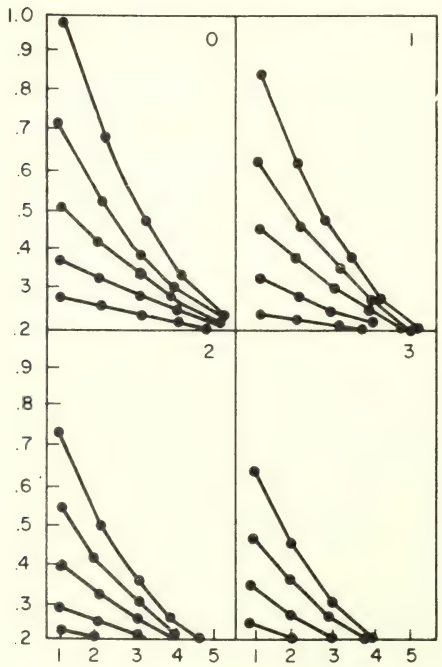

Figure 1.—Plot of row means from table as in Table 1 to determine form of functional relationship $A = f(X_1, X_2, X_3)$. In this figure, A is plotted on the Y-axis; X_1 is plotted on the X-axis; different values of X_2 are represented by the different lines in each panel, and different values of X_3 are represented by the four different panels (from **Watt 1967**).

obtaining tabulations as in table 1. After making such a table, he will plot families of graphs, as in figure 1. The order in which he then develops sub-sub-models to express the effects of X_1, X_2, X_3 on A will depend on the proportion of the variance in A accounted for by each of the X's. One should begin by modelling the effect of that independent variable for which the graph of A on X has the steepest slope and least scatter.

The researcher will then make various assumptions about the mode of operation of, say, X_3 on A, on the basis of his understanding of the phenomenon, and check these by examining the graphs. It is best to check assumptions systematically by asking oneself a series of questions, the answers to which form a logical branched tree. For example, using only a small list of questions, we form a logical tree as in figure 2. The following list of questions used in figure 2 could be expanded to make a tree from which all known equations could be derived.

1. Is dA/dX_3 proportional to X?
2. Is dA/dX_3 proportional to A? (i.e. are we dealing with some form of compound growth law?)
3. Is dA/dX_3 inversely proportional to X_3?
4. Does dA/dX_3 approach zero as A approaches some upper asymptote Amax?
5. Does dA/dX_3 approach infinity as X_3 approaches some lower limit X_3 min.?

Integral forms of some of the most commonly encountered equations are given below.

A—32	$Y = a + bX$
A—28	$Y = a + b \ln X$
A—24	$\ln Y = a + bX$, or $Y_x = Y_o e^{bx}$
A—16	$Y = a + bX - cX^2$
A—20	$Y = aX^b$
A—22	$Y = \frac{Y_{max}}{1 + e^{c-bx}}$ the logistic
A—30	$Y = Y_{max}\ (1 + e^{-bx})$

Once an elementary equation has been chosen to describe the effect of X_3 on A, this equation is integrated (using tables of integrals, if necessary), and transformed into a form suitable for testing. Graphical testing of the validity of the equation is done

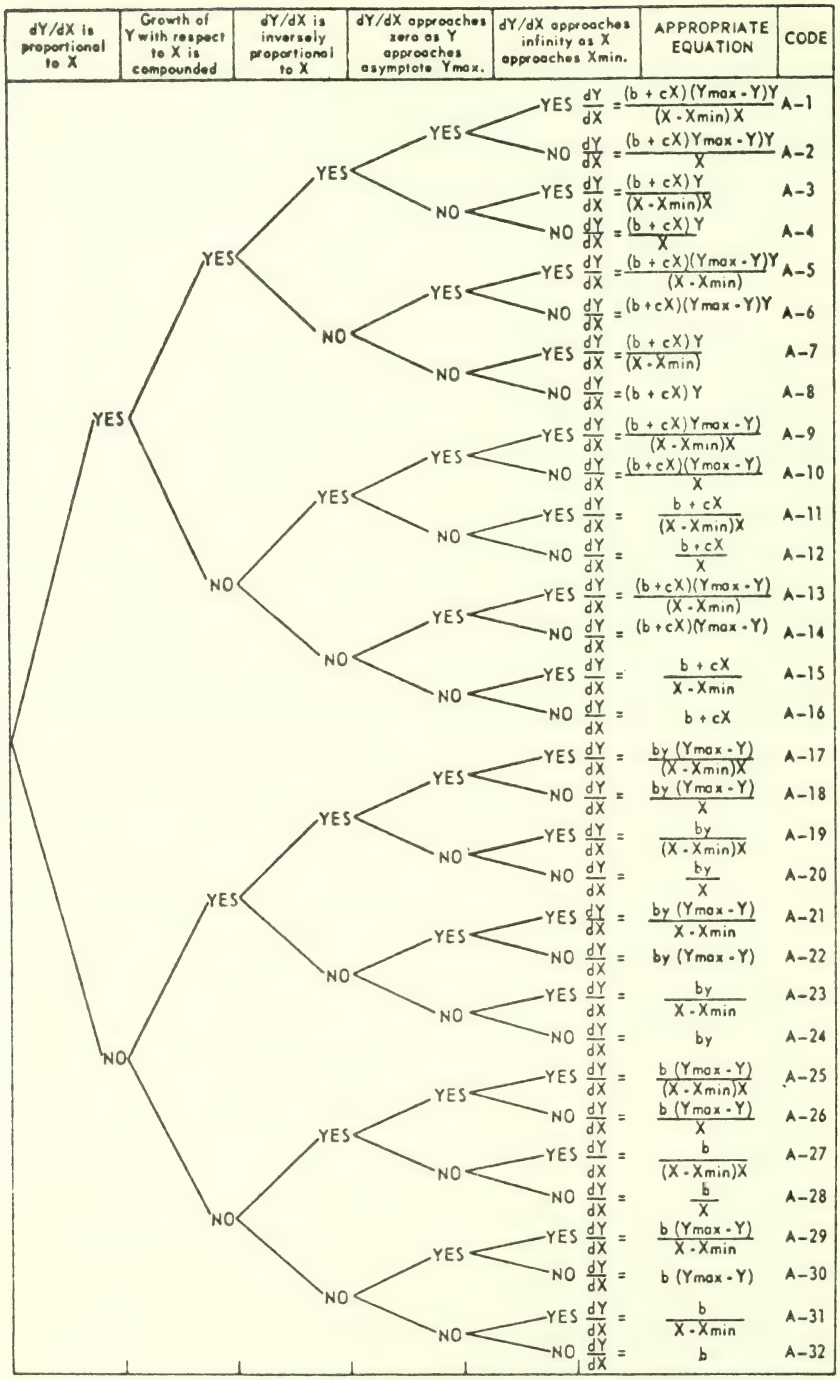
dY/dX is proportional to X
Growth of Y with respect to X is compounded
dY/dX is inversely proportional to X
dY/dX approaches zero as Y approaches asymptote Ymax.
dY/dX approaches infinity as X approaches Xmin.
APPROPRIATE EQUATION
CODE
A-1 dY/dX = (b + cX)(Ymax - Y)Y / (X - Xmin)X
A-2 dY/dX = (b + cX)Ymax - Y)Y / X
A-3 dY/dX = (b + cX)Y / (X - Xmin)X
A-4 dY/dX = (b + cX)Y / X
A-5 dY/dX = (b + cX)(Ymax - Y)Y / (X - Xmin)
A-6 dY/dX = (b + cX)(Ymax - Y)Y
A-7 dY/dX = (b + cX)Y / (X - Xmin)
A-8 dY/dX = (b + cX)Y
A-9 dY/dX = (b + cX)Ymax - Y) / (X - Xmin)X
A-10 dY/dX = (b + cX)(Ymax - Y) / X
A-11 dY/dX = b + cX / (X - Xmin)X
A-12 dY/dX = b + cX / X
A-13 dY/dX = (b + cX)(Ymax - Y) / (X - Xmin)
A-14 dY/dX = (b + cX)(Ymax - Y)
A-15 dY/dX = b + cX / X - Xmin
A-16 dY/dX = b + cX
A-17 dY/dX = by (Ymax - Y) / (X - Xmin)X
A-18 dY/dX = by (Ymax - Y) / X
A-19 dY/dX = by / (X - Xmin)X
A-20 dY/dX = by / X
A-21 dY/dX = by (Ymax - Y) / X - Xmin
A-22 dY/dX = by (Ymax - Y)
A-23 dY/dX = by / X - Xmin
A-24 dY/dX = by
A-25 dY/dX = b (Ymax - Y) / (X - Xmin)X
A-26 dY/dX = b (Ymax - Y) / X
A-27 dY/dX = b / (X - Xmin)X
A-28 dY/dX = b / X
A-29 dY/dX = b (Ymax - Y) / X - Xmin
A-30 dY/dX = b (Ymax - Y)
A-31 dY/dX = b / X - Xmin
A-32 dY/dX = b

Figure 2.—Logical branching tree for obtaining appropriate differential equation to describe a set of data (Watt, 1961).

as follows. Suppose we decide that $A - 30$ describes the effect of X_3 on A, while X_1 and X_2 are held constant.

That is

$$\frac{dA}{dX_3} = b\,(A_{max} - A),$$

and integrating,

$$-\ln(A_{max} - A) = bX_3 - \ln A_{max}$$

and since we wish first to see if b is indeed constant, this can be rearranged to yield

$$\ln\left[\frac{A_{max}}{A_{max} - A}\right] = bX_3 \qquad (6)$$

Plotting the transformed data on semi-logarithmic graph paper will yield a straight line if (6) in fact describes the relation between A and X_3, X_1 and X_2 being held constant. If a straight line is not obtained, some other elementary equation will be needed in place of $A - 30$. If there is rectilinearity, we proceed to the next step. This consists of plotting the data in terms of some other independent variable, say X_2.

We plot

$$Z = \ln\frac{\left(\frac{A_{max}}{A_{max} - A}\right)}{X_3} \text{ against } X_2$$

If plotting this transformation against X_2 yields a straight line parallel to the X_2 — axis, X_2 has no significant effect on A. Otherwise, we know that b is not a constant, but in fact is some function of X_2. If so, we decide for X_2 the appropriate form of the function, and test this guess by plotting the appropriate transformation to see if we get a straight line. For example, if we decide that

$$\frac{dZ}{dX_2} = \frac{cZ}{X_2},$$

then

$$Z = gX_2^{\,c},$$

which we test by plotting Z against X_2 on log-log graph paper.

If we get a straight line, we know that

$$\ln\left[\ln\frac{\left(\frac{A_{max}}{A_{max} - A}\right)}{X_3}\right] = \ln g + c\ln X_2$$

In this case, we can proceed to determine the effect of X_1 on A. We do this plotting

$$\frac{\ln\left(\frac{A_{max}}{A_{max} - A}\right)}{X_3 X_2^c} \quad \text{against } X_1.$$

When this step is complete, we solve the resultant form for A. The other sub-models are handled in the same way, and finally the whole model is put together.

Now that the basic process of cyclical model building and testing has been explained, there are a large number of questions on detail that need to be considered.

First, where we have made the postulate that A is a function of X_1, X_2 and X_3, how do we determine the order in which we will test the significance of X_1, X_2 and X_3? In fact, we proceed as in stepwise multiple regression, and examine the effects of the independent variables starting with the most important and proceeding to the least. The reason for proceeding in this sequence has to do with the logic of statistical testing (by leaving the least significant variables until last we have stronger error terms with which to test the significance of the first variables removed, using the variance-ratio, or F test).

Second, how do we decide the fundamental structure of the whole system model into which we incorporate terms for sub-models, into which we have in turn built sub-sub-models? One way of splitting up a model for a system is to structure it in terms of time. Consider, for example, an equation to account for the change in numbers of an insect population from one generation to another. First, we need to define a number of symbols.

Let	N_t	Represent the density of adult insects present immediately prior to oviposition in year t.
	N_{t+1}	The density of adult insects present at the corresponding time in year $t + 1$.
	$T_{t:t+1}$	N_{t+1}/N_t, i.e. the trend index of the population from t to $t + 1$.
	P_t	The proportion of N_t consisting of females that oviposit at t.
	F_t	The mean fecundity of the N_tP_t females.

S_E	The proportion of the eggs surviving to eclosion.
S_I, S_{II}.....S_{VI}	The proportion surviving of first instar larvae, second instar larvae . . . sixth instar larvae.
S_P, S_A	The proportion surviving of pupae and adults, respectively. Adult populations are measured just before oviposition in year $t + 1$.

We have, then, the model

$$T_{t:t+1} = \frac{N_{t+1}}{N_t} = P_t F_t S_E S_I \ldots\ldots S_{VI} C_p S_A.$$

This equation structures our system in a common-sense sequence, and is called a model. It is built up out of terms such as

$$S_E = f(X_1, X_2, X_3, X_4 \ldots\ldots X_n)$$

which are called sub-models, and these in turn may be built up out of sub-sub-models, which for example relate the variate value of X_4 to factors which govern X_4.

Another matter needing consideration is the list of five questions which produced the 32 (2^5) equations in figure 2. The list is, in fact, by no means complete, but was merely presented to show that most of the simple, commonly encountered differential equations can be derived from a simple logical branching tree. Biologists will be able to think of a variety of other questions which might be asked to expand the logical tree enormously. However, it is much easier to think of a differential equation than to solve it, and the biologist will need a powerful aid if he does much of this type of model-building. Apart from the usual handbooks, the most useful such aid is the compendium of methods of solution by Murphy *(1960)*.

A logical branching tree is not the only way to arrive at the equation which best describes a particular process *(Turner, Monroe and Lucas 1961; Turner, Monroe and Homer 1963)*. Another approach is to make use of general underlying equations from which a great variety of commonly-used models may be derived as special cases. Using such formulas, we can employ curve-fitting techniques to determine the values of various parameters that

give best fit of the general equation to a particular body of data. The particular values the parameters take indicate which of the special cases we are dealing with. To illustrate, consider the differential equation used by Turner and his associates, in which n and ε are variables, δ, a, and γ are parameters.

$$\frac{dn}{d\varepsilon} = \frac{\delta(n\text{-}a)}{\varepsilon - \gamma\delta}$$

This equation integrates to produce

$$n = a + \beta\ (\varepsilon - \gamma\delta)\ \delta \qquad (7)$$

The constant α determines which special case we have represented in our data. If β is a positive integer, we have a polynomial process, which is non-linear if δ exceeds one. As δ approaches either positive or negative infinity, (7) approaches the exponential model

$$n = a + \beta\, e^{-\varepsilon/\gamma}$$

The following values of $2/\delta$ produce the given simple models

$2/\delta$	model
-4	inverse square root law
-3	inverse two-thirds law
-2	rectangular hyperbole
-1	inverse square law
0	exponential
1	parabola
2	straight line

When $2/\delta$ is negative, the curves have two asymptotes, when $2/\delta$ is zero they have one, and when $2/\delta$ is positive they have no asymptotes.

Another such basic equation has been proposed by Grosenbaugh (1965).

$$\text{Consider} \quad Y = H + A\left[e^{(N^2\text{-}1)U} \quad -NU\right]^{NM+1} \qquad (8)$$

where U represents a 1- or 2-parameter function such as

$$U = E^{-B(X-G)} \qquad (9)$$

Equation (8) with variant (9) inserted takes the form of almost all well-known mathematical functions for two variables,

depending on the values assigned to N and M. The idea behind Grosenbaugh's research is to facilitate the computations for iterative regression by developing tables of the partial derivatives used for each of the elementary functions corresponding to a particular N and M pair of values. This suggests a large-scale computer routine for doing iterative regression, in which the computer starts with only the raw data. In the first part of the program, the computer determines the values of N and M and the form of U. Then, using these three pieces of information, it selects from memory the appropriate derivatives for calculating the values in the set of equations. The second part of the program is the iterative regression routine.

It should be noted that both the logical branching tree method and the general equation method suggest means of programming a computer so that it decides which model best describes a given body of data.

Model-building techniques of the type we have described can obviously lead to extremely complicated models. The question naturally arises as to how one can perform logically valid statistical or other tests on the model, to determine how accurately it describes reality. One approach is to test the whole model statistically piece by piece (sub-model or sub-sub-models separately), using iterative regression where necessary because parameters enter the sub-models nonlinearly. However, this approach has a logical weakness, in that we lose a degree of freedom every time a new parameter enters an equation, and our error terms in statistical tests lose strength. This means, that as our models become more and more complex, it becomes progressively more difficult to demonstrate statistically that they do not in fact describe the data. In other words, ANY sufficiently complicated model is a highly flexible interpolatory formula, even though its structure bears no relationship to the structure of the process we are trying to describe.

The reader can satisfy himself on this point by noting in tables of F-values, that the smaller the number of numerator degrees of freedom, the higher the F-value must be to produce significance at a given probability level. To circumvent this degrees-of-freedom

impasse, the following procedure is suggested. Obtain data from one set of surveys, or experiments on components of whole systems, then build a systems model. The model is then tested by seeing how it can predict the outcome from another set of surveys or experiments on whole systems, or of a different type. No degrees of freedom are lost in such a test. For example, we might build a systems model describing a historical process, using data from experiments on particular components of the whole process. Then having used these sub-models to build the whole model, the model is tested against data on the history of the whole system. Such an approach has been used by Holling *(1966)* and Watt *(1955)*.

This concludes a general discussion on methods of developing models. A typical situation that arises subsequent to following the steps outlined is for the researchers to find that their systems model only accounts for 40 per cent of the variance in the system under study. It often develops that a major proportion of the entire model-building effort is expended on efforts to refine the initial systems model. A number of procedures are available to help with this step.

1. Using the model, obtain values of "Y calculated" for each case on which data were obtained. Then make a large graph in which "Y calculated" values are plotted against "Y observed." Every point on the graph should be labeled as to the characteristics of the sample that produced the datum. When all points are plotted, we study the graph to observe if particular sets of sample values deviate consistently above or below the 45° line on which all points would lie in an error-free situation, and where we have an accurate model. Such sets of values may provide clues about factors omitted from the analysis which should have been measured.

2. Another method for discovering structural weakness in the model is to plot "Y observed -Y calculated" against each of the independent variables in turn. Systematic departures from a straight line parallel to the X- axis indicate that a term in the model does not mimic nature accurately.

3. A third source of difficulty in a systems model occurs if one

or more variables have been incorrectly measured, defined, or coded. Suppose we know from field experience that torrential downpours or high-velocity wind gusts can drive delicate insects off their food plants onto the ground where they may starve or be drowned. It is not adequate to express the force of such factors in standard meteorological units, such as inches of rain collected in a rain gauge or miles of wind per hour moving past a stationary point. Rather, we should record and enter into our equations the biologically relevant variables: maximum drop velocity within a 24-hour period or maximum gust velocity.

4. If some of the independent variables that entered into multiple regression analyses were of the form X_1X_2, then computer output may reveal that the cross-product or other interaction terms are needed in the systems model.

The Experimental Components Approach

The preceding discussion outlined mathematical techniques by which one could develop a model for a system on which a large body of data had already been collected. However, such a procedure is only useful as a "macro" approach. In order to obtain the kind of insight into the mechanics of a system that will allow us to manipulate it profitably, in many cases more detailed information about the quantitative nature of processes will be required than those available from field studies. Further, the "macro" approach, typical of field studies, limits us to the ranges of variate-values provided by nature. Hence, in many cases a "micro" approach is called for in addition to the "macro" approach. Holling *(1961, 1965)* has presented an elaborate exposition of the logic and methodology of the "micro" approach, which he calls experimental components analysis. The following discussion is based in part on his publications.

The essence of the experimental components approach is that the processes of experimentation and mathematical model construction are conducted as two interlocking parts of an integrated program. A systems model grows out of a sequence of steps which proceed as follows.

The process which we wish to study (e.g. predation, parasitism,

dispersal, reproduction) is conceived of as comprising a set of component processes, or constituent fragments. We determine by experiment and observation what these fragments are for the process in question, then through *a priori* considerations sort them into two groups, basic and subsidiary. A basic component of a process is a constituent factor that invariably operates where that process occurs. For example, prey density and predator density must always operate where predation occurs. On the other hand, predator speed is a subsidiary component, because it is not relevant in the case of an ambush predator, or a filter-feeder, or a Portuguese man of war. In short, we assume that for any process, such as predation, there is a basic model that explains the underlying processes common to all species pairs of predators and prey. We further assume that the great diversity of different predator-prey processes is caused by the additions to this basic model that occur in various situations as subsidiary components. Hence, a sequence of experiments is conducted, beginning with experiments on a small group of basic components of a process. The experiments are designed to analyze the operation of these components in sufficient depth that a mathematical model can be built to describe the operation of the components. The model is so chosen as to meet two desiderates: it must give a statistically satisfactory fit to the data and it must incorporate real insight into the phenomenon.

Additional experiments are conducted until all the basic components of the process have been analyzed, modelled, and incorporated into a systems model. Then the whole process is repeated for the various subsidiary components that can be found in the various situations where the type of process under study occurs. Finally, a systems model is constructed which can be used to simulate the process on a computer. Any particular instance of the process (representing a particular variant of the model) can be simulated, merely by informing the computer, by means of control and parameter cards, which terms are to be added to the basic model, and what values the relevant parameters are to take.

The preceding is a very general description of what is in practice a highly complex experimental and mathematical pro-

cedure. In order to give any real insight into the kind of reasoning used in the experimental components approach, it is necessary to describe a particular application. Holling's program on predation will be explained so as to bring out the sequence of steps in his reasoning.

Holling first decided, on the basis of his own observations, experiments on many predator-prey systems, and study of the literature that five groups of variables affect predation:

density of the prey species
density of the predator species
characteristics of the prey species
characteristics of the predator species
characteristics of the environment.

The first two variables must operate in every predator-prey situation, and hence are basic variables. There are situations in which the last three groups of variables do not affect predation; therefore they are subsidiary. The two basic factors can each have their effect through numerous causal pathways. Thus, there are four components of the response to prey density by predators, each of which can be subdivided as follows:

(1) Searching rate —predator speed relative to prey speed
  —the maximum distance from a predator at which it notices and attacks a prey, and the effect of hunger on this distance.
  —the proportion of attacks that result in successful capture.
(2) The time predators are exposed to prey
  —time predators spend in non-feeding activities.
  —time predators spend in feeding activities.
(3) Time spent handling each prey
  —time spent in pursuit for prey
  —time spent eating
  —digestive pause, while predator is not hungry enough to attack
(4) Hunger
  —rate of digestion and assimilation
  —maximum food capacity of the gut

Experiments are designed to obtain the form of, and parameter

values in mathematical equations for each of these components and sub-components. As such equations are developed, they are incorporated into a systems model which is carefully checked against experimental data on the whole system. Finally, the systems model, when complete, serves as the basis for computer simulation and optimization studies. These give rise to new insight about the most important criteria for evaluating biological control agents, and the most effective parameter values for these criteria.

A similar components analysis can be conducted for any type of complex process in the ecology-behavior domain. It should be emphasized that the key concept in this whole approach is the intimate reciprocal feedback between the experimental program and computer analysis and simulation, with the model arising from one type of data and being subjected to test against other data at each stage in its development. Whenever the simulation studies predict a result not corroborated by experiment, the model clearly needs re-examination.

Literature Cited

Goldberg, S.
1958. Introduction to difference equations. N. Y. Sci. Editions, John Wiley and Sons.

Grosenbaugh, L. R.
1965. Generalization and reparameterization of some sigmoid and other nonlinear functions. Biometrics 21:708-714.

Holling, C. S.
1961. Principles of insect predation. Annu. Rev. Entomol. 6:163-182.

Holling, C. S.
1965. The functional response of predators to prey density and its role in mimicry and population regulation. Entomol. Soc. Canada Mem. 45.

Holling, C. S.
1966. The functional response of invertebrate predators to prey density. Entomol. Soc. Canada Mem. 48.

Murphy, G. M.
1960. Ordinary differential equations and their solutions. Princeton, N. J. D. Van Nostrand.

Turner, M. E., R. J. Monroe, H. J. Lucas, Jr.
1961. Generalized asymptotic regression and non-linear path analysis. Biometrics 17:120-143.

Turner, M. E., R. J. Monroe, and L. D. Homer.
1963. Generalized kinetic regression analysis: hypergeometric kinetics. Biometrics 19:406-428.

Watt, K. E. F.
1955. Studies on population productivity. I. three approaches to the optimum yield problem in populations of tribolium confusum. Ecol. Mongr. 25:269-290.

Watt, K. E. F.
1959. A mathematical model for the effect of densities of attacked and attacking species on the number attacked. Canad. Entomol. 91:129-144.

Watt, K. E. F.
1967. Ecology and resource management. McGraw-Hill Book Co., N. Y.

DYNAMIC MODELS FOR POPULATION SYSTEMS

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STUDENTS of forest insect population dynamics have been remarkably slow in adopting those mathematical methods that have been widely developed in the study of other dynamic systems. I think that most of us have been seduced by statistical methods and, as a result, have been intensively engaged in making careful measurements and analyses without having given any rigorous thought to the logical structure of the system we are concerned with. We have been guided by our intuition in choosing system parameters for study.

In this paper I will discuss the mathematical structure of some forms of dynamic system models. There are two objectives to the discussion. First, I hope to show that the construction of a mathematical system model will provide all the relevant information about the system—whether our interests are in understanding the biological structure, in applying regulation, or in predicting system behavior. Second, I hope to make clear that the construction of a system model will give the best possible guide to system dynamics research by focusing effort on the measurement of important system parameters rather than relying upon intuition to serve as is generally the case at present.

System Models

It is convenient to use as a point of departure, the population change model:

$$N_{t+1} = \prod_{i=1}^{h} S_i \cdot P \cdot F \cdot N_t \qquad (1)$$

where N_t is number at time t, S_i is survival during age interval i, P is proportion of adults that are female, and F is fecundity.

It is interesting that this equation represents the most advanced form of our thinking about population system dynamics today. The interest arises because it is so patently incomplete, as will be seen shortly.

Equation (1) is a *difference equation* model for a population system. In simplest form, where each member of a population produces in a unit of time k individuals, and a proportion m of the individuals present at time t dies in a unit of time, we find

$$N_{t+1} = kN_t - mN_t \qquad (2)$$

If we knew the values of k and m and the initial value of N, we would be able to calculate the number at any time thereafter. That is, from (2) it would be possible to obtain a numerical solution for N as a function of time. In fact, this is our objective in constructing a system model: we want to know how the system will behave over time so that we can regulate it, harvest from it, and so forth. Now, a numerical solution might be perfectly acceptable, but in this case it is possible also to obtain an analytic solution:

$$N = f(t)$$

where $f(t)$ is a function of time defined on integral values of t. To find f in this case, we proceed:

$$\text{Given (2)}: N_{t+1} = kN_t - mN_t \ , N_{t=o} = N_o$$
$$\text{Then: } N_{t+1} = (k\text{-}m)\ N_t \qquad (2a)$$
$$\text{or: } N_{t+1} - (k\text{-}m)\ N_t = 0$$

Assume that $N = Cx^t$, such that if C and x were known, a solution could be found. To find C and x, assume this solution and substitute in (2a):

$$Cx^{t+1} - (k\text{-}m)\ Cx^t = 0$$
$$Cx^t\,[x - (k\text{-}m)\,] = 0$$

Since: $Cx^t \neq 0$

Then: $x - (k\text{-}m) = 0$ and $x = k\text{-}m$

To find C:

Since: $N_{t=o} = N_o$

Then in: $N = Cx^t$

$N_o = Cx^\circ$

or $C = N_o$

Therefore: $N = N_o\ (k\text{-}m)^t$ is the desired solution (figure 1).

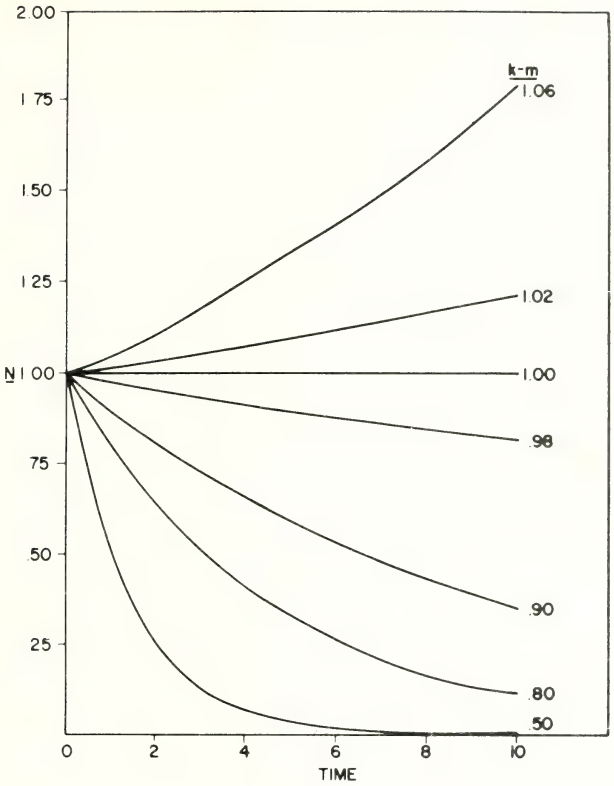

Figure 1.—Solution of the difference equation $N_{t+1} - (k\text{-}m)N_t = 0$, for given values of (k-m).

It would be unusual to encounter such a simple system. Mortality usually depends upon other system elements such as predators, parasites, and disease organisms. Thus, if P represents, say, predator abundance, and in a unit of time each predator kills h of organism N, we would obtain:

$$N_{t+1} = kN_t - hP_t \qquad (3)$$

However, in order to obtain a numerical solution in this case, we must know the value of P at each time t, P_t. Clearly, the system model is incomplete unless we know how P changes over time. This is exactly why the model in (1) is so deficient: it says nothing whatever about the many elements other than N present in the system. Thus, the substantial effort currently devoted to field studies with the objective of measuring the components of

(1), which ignore in large part the other system components, will produce seriously incomplete knowledge about the system.

A complete system model in the present case would consist of equation (3) and an equation for P. Suppose that during a unit of time a proportion r of P dies, and that each N permitted s progeny of P to be produced (s would be a complex parameter that included the probability of encounter between N and P and the reproductive rate of P). The following set of equations would then describe the system:

$$\left.\begin{array}{ll} N_{t+1} = kN_t - hP_t & N_{t=o} = N_o \\ P_{t+1} = sN_t - rP_t & P_{t=o} = P_o \end{array}\right\} \quad - \qquad (3a)$$

Here, too, it is possible to obtain a numerical and an analytic solution for N and P over time.

We have now progressed to the point where the structure of a dynamic system model can be appreciated. It consists of these fundamental elements:

a. equations that state how each variable in the system changes *over time* — dynamic equations that incorporate:

b. the interrelationships among system elements described by static equations.

This deserves some amplification. A great deal of biological research has been devoted to obtaining the material in (b) above. The relationships between the number of attacked hosts and host density, parasite/predator density, spatial distribution of each organism, and so forth are fairly well known in some circumstances. Relationships between reproductive capacity and food quality and quantity, temperature (or "heat units"), and so forth are similarly known. In fact, the description of such relationships seems to be the main objective of many population studies, and both field studies and behavioral, genetic, and physiological studies in the laboratory have produced a large catalog of relationships of this kind. However, it is important to realize that the study of system dynamics depends critically upon such relationships being incorporated into mathematical descriptions of the way in which systems change *over time*. Thus, static relationships must be of suitable form to be incorporated

into dynamic equations and, in order for the dynamic model to be constructed for any system, all such relevant relationships must be known. It follows that early in the establishment of system studies thought must be devoted to the form of the system model.

The difference equation models discussed above are particularly simple; they are linear models. In general, system models will be non-linear. The distinction lies in the form of the equations. For any model in which variables occur only to the first power, no products of variables occur, and variables do not appear as exponents, the model is said to be linear. Analytic solutions to linear models can be found. In general, this is not possible for non-linear models. However, numerical or graphical solutions can always be obtained.

As an example of a non-linear difference equation model, consider the following much simplified case. Suppose we are dealing with an insect like the white pine weevil (W) which attacks white pine leaders (P). Suppose that the number of leaders that will be attacked in any season depends upon the number of weevils present. That is, as the weevil population increases, intraspecific competition intensifies for attack sites and the increase in the number of attacks per weevil declines. A simple function to describe (approximately) this sort of curve would be:

$$A_t = W_t \left\{ 1 - \exp\left(-b \frac{P_t}{W_t}\right) \right\} \tag{4}$$

where A is the number of leaders attacked in a given year and b is a constant. Suppose, furthermore, that 2 years are necessary before an attacked leader again enters the leader population. Then, the following difference equation could be constructed for leader population dynamics:

$$P_{t+1} = P_t - A_t + A_{t-1}$$

$$= P_t - W_t \left\{ 1 - \exp\left(-b \frac{P_t}{W_t}\right) \right\} + W_{t-1} \left\{ 1 - \exp\left(-b \frac{P_{t-1}}{W_{t-1}}\right) \right\} \tag{5}$$

In order to construct an equation for weevil population dynamics, let us suppose that each attack in a season produces

a constant number, k, weevils in the next season. Thus:

$$W_{t+1} = kW_t \left(1-e^{-b \frac{P_t}{W_t}}\right) \qquad (5a)$$

Thus, (5) and (5a) together with initial values constitute a complete system model. It is non-linear since the variable W appears in the exponent of both functions. Some solutions for this model are shown in figure 2.

Besides the non-linearity, an additional element characteristic of biological systems has been introduced—a time-lag in the form of an effect in the present season of events that took place in a previous season. That is, leader numbers have changed partly because of attacks in the present year and partly because of the intensity of attack in previous years. Time lags introduce a particularly interesting feature to such systems; they can account by themselves for oscillation in an otherwise non-oscillatory system. In effect, the time lag changes the "order" of the equation

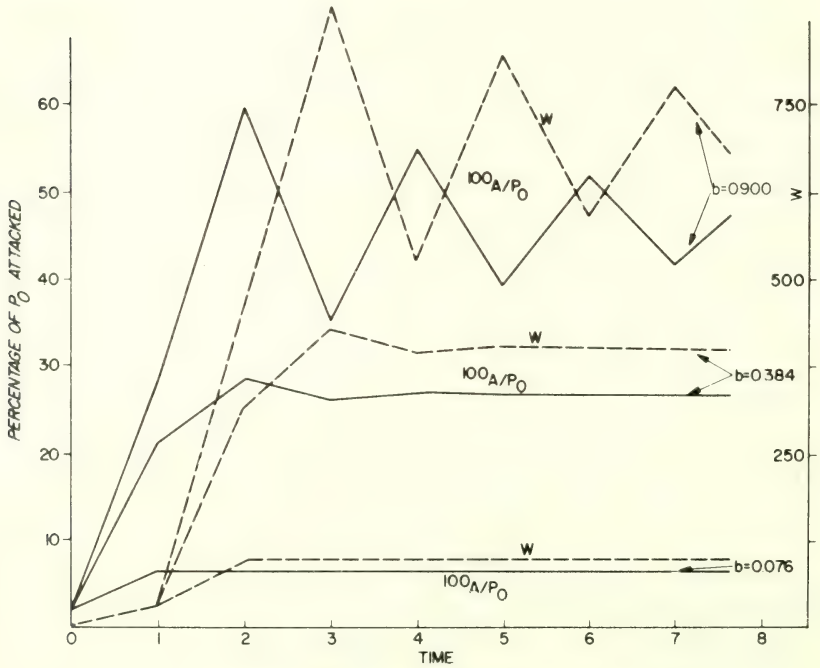

Figure 2.—Solutions of equations 5 and 5a showing behavior of the system over time.

from first to second. As a simple example of this phenomenon, consider the following general single variable system model:

$$Y_{t+1} + aY_t + bY_{t-1} = 0$$

Assume, as in equation 2a, that: $Y = Cx^t$

$$CX^{t+1} + aCx^t + bCx^{t-1} = 0$$
$$Cx^{t-1}(x^2 + ax + b) = 0$$
$$x^2 + ax + b = 0$$
$$\text{and } x = -\frac{a}{2} \pm \frac{\sqrt{a^2 - 4b}}{2}$$

Since there are two possible values for x, assume that the solution is a linear combination of the two, that is:

$$Y = C_1\left\{-\frac{a}{2} + \frac{\sqrt{a^2 - 4b}}{2}\right\}^t + C_2\left\{-\frac{a}{2} - \frac{\sqrt{a^2 - 4b}}{2}\right\}^t$$

Since $Y(o) = Y_o$ and $Y(-1) = Y_{-1}$, the initial conditions, we can obtain solutions for C_1 and C_2 by solving the two simultaneous linear equations obtained from substituting $t = o$ and $t = -1$.

There are several possible results depending upon the values of the coefficients a and b. If, for example, the two values of x are complex conjugates, the solution will oscillate.

Now, let us consider a second mathematical form for constructing system models—the *differential equation.* This is the most widely utilized mathematical form in the sciences. Using equation (2), $N_{t+1} = kN_t - mN_t$, we can consider the rate at which N changes per unit time. By definition, the average rate of change consists of the difference between final and initial values of N, divided by the time period over which the change took place. That is,

$$\frac{\Delta N}{\Delta t} = \frac{N_{t+\Delta t} - N_t}{\Delta t}$$

where ΔN is the increment in N and Δt the increment in t. Suppose we desired a representation for change in N that yielded intermediate values between integer values of t, either because we knew the system behaved in a continuous fashion (or nearly so, as in a bacterial population in a flask) or because there was some advantage in having such a continuous function (some of

the advantages will be apparent below). Since our objective is to obtain a continuous function, we assume that the changes in N are taking place continuously—that is, for any Δt, no matter how small, there will be some change in N. Formally, we are searching for the derivative of N—the "instantaneous rate of change" defined as

$$\underset{\Delta t \to 0}{\text{Limit}} \left\{ \frac{N_{t+\Delta t} - N_t}{\Delta t} \right\} = \frac{dN}{dt}$$

In the case of equation (2), we have shown the solution

$$N = N_o(k\text{-}m)^t$$

or, if $k - m = r$, $N = N_o r^t$

Let us now calculate the instantaneous rate of change in N:

$$\frac{dN}{dt} = \underset{\Delta t \to 0}{\text{Limit}} \left\{ \frac{N_o r^{t+\Delta t} - N_o r^t}{\Delta t} \right\}$$

$$= \underset{\Delta t \to 0}{\text{Limit}} \left\{ (N_o r^t) \quad \frac{(r^{\Delta t} - 1)}{\Delta^t} \right\}$$

$$= \left\{ \underset{\Delta t \to 0}{\text{Limit}} \quad (N_o r^t) \right\} \quad \left\{ \underset{\Delta t \to 0}{\text{Limit}} \quad \frac{r^{\Delta t} - 1}{\Delta t} \right\}$$

The value of the first factor is obviously $N_o r^t$, which in fact is N. In order to calculate the second limit, we resort to L'Hospital's rule and obtain:

$$\underset{\Delta t \to 0}{\text{Limit}} \left\{ \frac{r^{\Delta t} - 1}{\Delta t} \right\} = \underset{\Delta t \to 0}{\text{Limit}} \left\{ \frac{r^{\Delta t} 1n\, r}{1} \right\} = 1n\, r$$

Thus, we discover that

$$\frac{dN}{dt} = N\, 1n\, r \tag{7}$$

This is a differential equation in N. A solution to this equation would be obtained by integration and would yield

$$N = N_o \exp(1n\, r \cdot t) \tag{7a}$$

This function represents a smooth curve that passes through all the points generated by the difference equation (2).

Thus, differential equations can be viewed as approximations for difference equations, and in fact the converse also applies.

As demonstrated, the construction procedure for differential equation models for population systems is similar to that for

difference equations. A rate equation is constructed for each variable in the system. In general, these will be non-linear and involve such things as time lags and variable coefficients. One of the simplest and earliest such models is that of Lotka-Volterra. Where H and P are a host and parasite population, this model states that

$$\left.\begin{aligned} \frac{dH}{dt} &= (b - dP)H \\ \frac{dP}{dt} &= (rH - m)P \end{aligned}\right\} \qquad (8)$$

This is a simple non-linear model, for which a good approximate solution exists, yielding an oscillation in time of P and H (figure 3).

This and associated models have received a great deal of atten tion—far more than they warrant, perhaps. Even casual speculation about the model for a predator-prey system quickly leads to a much more complex set of functions. For example, both to illustrate this point and to illuminate further the construction of a dynamic system model in differential equation form, let us construct a hypothetical model.

To begin, consider that we are dealing with a closed system in which we have neither immigration nor emigration, so that all changes must occur through births and deaths. Next, in regard

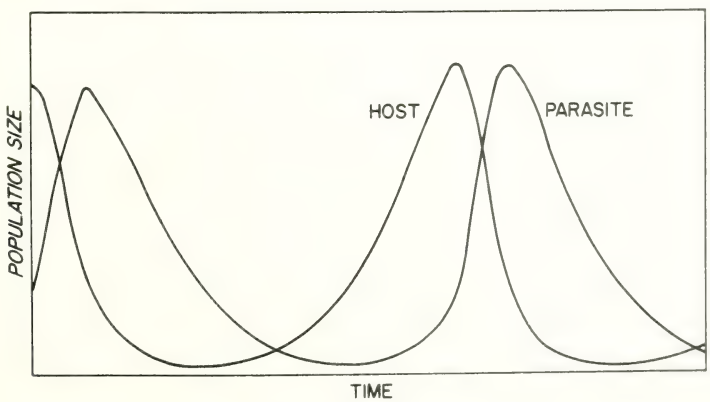

Figure 3.—Behavior of the Lotka-Volterra predator-prey model.

to host reproduction, it would be most unusual to discover that reproductive rates were constant. A more reasonable speculation would be that reproduction behaved as in the logistic equation:

$$B = \text{Birth Rate} = \frac{bH(K\text{-}H)}{K} \tag{9}$$

where H is population number, b the maximum reproductive rate, and K some constant representing the "carrying capacity" of the environment. Or, we might invoke a more complex model like that proposed by Watt *(1960)* as a general fecundity model. In any event, we would probably speculate that reproduction depended in some way upon density. Furthermore, it might be reasonable that it depended also upon temperature. In an environment in which temperature varied, temperature in turn could be considered a function of time, so that we might write

$$\begin{aligned} B &= f(t)\ \frac{(K\text{-}H)}{K} \\ &= f(t)H\ -\frac{f(t)\ H^2}{K} \end{aligned} \tag{10}$$

Here, we have a non-linear differential equation with variable coefficients. Furthermore, it might be reasonable to suppose that reproductive rates now depend upon the density of the host, H, some time ago $(t - \tau)$ since it takes time $(\tau$ units) for animals to mature. Thus, we might write:

$$B = f(t)\ H_{t-\tau}\left\{\frac{K\text{-}H_t}{K}\right\} \tag{11}$$

It would also be reasonable to speculate that K depended upon the food supply so that $K = g(F)$, and we would have to enter a third rate equation for F. Let us avoid this complication now.

Now, consider the death rate of the host. In the Lotka-Volterra model it is assumed to be a linear function of P. However, again because of the large amount of data available on the relationships between predators and prey, we know that this is almost certainly not the case. Rather, very likely as predator population increases relative to that of the host, predator efficiency decreases. We might utilize a function such as:

$$D = \text{Death Rate} = H(1 - \exp(-cP)) \tag{12}$$

or any other suitable function, such as from Holling *(1966)* or Watt *(1959)*. Then, we could write:

$$\frac{dH}{dt} = f(t)\, H_{t-\tau}\left\{\frac{K-H_t}{K}\right\} - H_t\left\{1 - \exp(-cP)\right\} \qquad (13)$$

Consider now predator dynamics. Let us assume that predator reproduction again behaved like the logistic except that in this case K depended upon H and that $K = h(H)$. Furthermore, we might presume that all predators of a certain age, a, died. We would then write:

$$\frac{dP}{dt} = bP_t - \frac{bP_t^2}{h(H_t)} - P_{t-a} \qquad (14)$$

Equations (13) and (14) make up a model for this rather simple system. It is obvious that the nature of biological material takes us very rapidly into rather complex models. We have neglected many kinds of phenomena that might be considered. For example, variation in the constants would result from evolution in the system; it is known that reproductive and mortality constants depend upon oscillatory genetic changes that result from differential mortality over time. Also, probably few systems are really closed, and almost any system can be enlarged as variables are added to include the whole world. However, ultimately, the addition of more variables will have little effect on the system, and its dynamics will depend upon the effects of a few most important variables. The problem of discerning relative importance of variables obviously depends upon obtaining a knowledge of the system—and thus upon constructing its model.

Obtaining A Solution for the Model

Let us now turn to the matter of studying system behavior, given that its model is available. The easiest way to accomplish this is to obtain an analytic solution and study its form. In several cases considered above this has been done, and in any linear case an analytic solution can be found. Since in many real systems it is possible to find a linear model that is a good approximation to the real non-linear case over some operating range, it is worth

acquiring the rather elementary mathematics to obtain such solutions. Furthermore, since most population system models will be of first-order (in contrast to some physiological models in which the application of mechanical principles yield higher order equations) the very limited mathematics can be stated in a few paragraphs.

Given a linear system:

$$\frac{dx_1}{dt} = a_{11}\,x_1 + a_{12}\,x_2 + \ldots + a_{1n}\,x_n$$

$$\frac{dx_2}{dt} = a_{21}\,x_1 + a_{22}\,x_2 + \ldots + a_{2n}\,x_n$$

$$\vdots$$

$$\frac{dx_n}{dt} = a_{n1}\,x_1 + a_{n2}\,x_2 + \ldots + a_{nn}\,x_n$$

With given initial conditions $x_i(o)$, the system model can be written in matrix form as:

$$\begin{pmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \\ \vdots \\ \frac{dx_n}{dt} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

The solution to the set of equations consists of a set of functions:

$$x_i = C_{1i}\exp(\lambda_1 t) + C_{2i}\exp(\lambda_2 t) + \ldots + C_{ni}\exp(\lambda_n t) \quad (15)$$

where the C_{ij} depend upon initial conditions, and the λ are the eigenvalues of the a_{ij} matrix (providing the eigenvalues are distinct; otherwise the result is only slightly more complicated.)

The eigenvalues of the matrix are obtained by solving the polynomial equation that results from taking the determinant of the a_{ij} matrix minus λ times the identity matrix and setting it equal to zero. To illustrate:

Given:

$$\begin{pmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \end{pmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \qquad \begin{aligned} x_1(o) &= x_{10} \\ x_2(o) &= x_{20} \end{aligned}$$

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = 0$$

$$\begin{bmatrix} a_{11}-\lambda & a_{12} \\ a_{21} & a_{22}-\lambda \end{bmatrix} = 0$$

$$(a_{11} - \lambda)(a_{22} - \lambda) - a_{21}\, a_{12} = 0$$

$$\text{or } \lambda^2 - (a_{11} + a_{22})\lambda + (a_{11}\, a_{22} - a_{21}\, a_{12}) = 0 \qquad (16)$$

This is a quadratic equation in λ of the form:

$$\lambda^2 + b\lambda + c = 0$$

that has roots:

$$\lambda_1 = \frac{-b}{2} + \frac{\sqrt{b^2 - 4c}}{2}$$

$$\lambda_2 = \frac{-b}{2} - \frac{\sqrt{b^2 - 4c}}{2}$$

Systems of larger size pose no particular difficulty. In order to interpret the results, it is necessary to be able to change complex roots to trigonometric form (which implies some oscillation in the solution), but in general the solutions are straightforward. Depending upon the form of the non-linearity in the model, some analytic procedures will yield solutions in the form of series. There are also graphical (isocline) methods, but they are limited to second order systems.

However, one does not really have to know any mathematics in order to solve any of these models; solutions can be obtained on either an analog or digital computer. Thus, where the biologist 15 years ago had to turn to a trained mathematician (if he could find one, if he could communicate with him, and if he could understand the answers given), today, simply by learning to program a computer, a task of about the same complexity as learning first year high-school algebra, he can perform more complete analyses of most mathematical problems.

Consider, for example, the matter of programming for an analog computer. This device can add, multiply, and integrate with respect to time, and perform the inverse operations. Given a model such as that of Lotka-Volterra, one simply supplies to the integrators (a particular component on the machine) the values of the derivatives (in the form of electrical signals, the voltage of which is proportional to the variable) and obtains the values of the variables. Since the values of the derivatives consist of combinations of the variables, the input signals are obtained from the output. Figure 4 shows a circuit for solving this model. Since the electronic analog computer is a continuous device, it solves differential equations directly.

It is difficult to simulate time lags on the analog computer, and it also is difficult to develop some of the more complex static functions. The digital computer can easily be programmed to provide these elements, and it is also possible to integrate numerically to any desired degree of accuracy. A number of numerical integration methods have been developed—Euler, Runge-Kutta, and Adams methods, to name a few—and they are easily programmed if they are not readily available as subroutines.

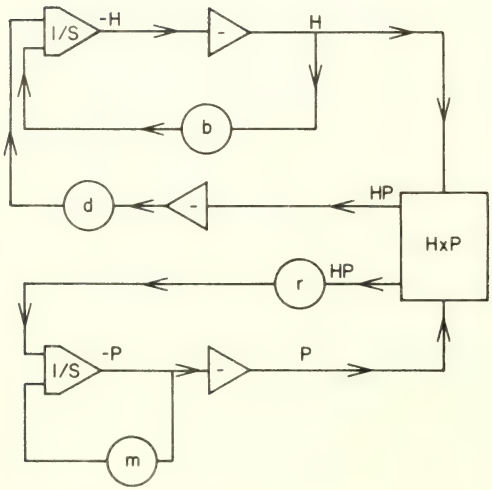

Figure 4.—Analog computer circuit for solving the Lotka-Volterra equations.

Fundamentally, these methods use the derivative as an estimate of the slope of the function at any time and predict the next value of the function as a linear excursion with this slope.

At the new value, prediction backwards is made and appropriate corrections employed if the original and predicted values do not agree. The correction procedure varies among the several methods, but they are all designed to converge upon the true value of the function within some stated accuracy limits.

Stability Analysis

There is an important analytic area that can be pursued when analytic solutions for the system model cannot be found. This is the matter of system stability. It may be of interest to discover how the system will behave if it reaches the neighborhood of an equilibrium point. An equilibrium point is defined as the set of values of the system variables at which the rates of change are zero—and thus a point at which the system does not change over time. However, since there is always "noise" in any real system, displacements from the equilibrium point will generally occur. If after displacement, the system returns to the equilibrium point, it is said to be stable; if it diverges, it is unstable; and if it remains in the neighborhood of the point (say, oscillates about it) it is marginally stable. A great deal of information about system behavior can be obtained from an analysis of its stability at all equilibrium points.

To investigate stability, one first solves for the values of the equilibrium points by using the simultaneous equations:

$$\frac{dx_1}{dt} = f_1(x_i, t) = 0$$

$$\frac{dx_2}{dt} = f_2(x_i, t) = 0$$

$$\vdots$$

$$\frac{dx_n}{dt} = f_n(x_i, t) = 0$$

Then, a linearized model for small perturbations, Δx_i, in the x_i is obtained by constructing the Jacobean matrix:

$$\begin{pmatrix} \frac{d\Delta x_1}{dt} \\ \frac{d\Delta x_2}{dt} \\ \cdot \\ \cdot \\ \cdot \\ \frac{d\Delta x_n}{dt} \end{pmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta x_n \end{pmatrix}$$

and evaluating it at the equilibrium point. The behavior of the system in the neighborhood of the equilibrium point is equivalent to that of the linearized model.

To illustrate, consider the Lotka-Volterra model:

$$\frac{dH}{dt} = f_1 = (b\text{-}dP)H \qquad b,d,r,m > 0$$

$$\frac{dP}{dt} = f_2 = (rH\text{-}m)P$$

Equilibrium points E_1 and E_2 are at:

$$(b\text{-}dP)H=0$$
$$(rH\text{-}m)P=0$$

$$E_1: \begin{cases} H=0 \\ P=0 \end{cases} \qquad E_2: \begin{cases} P = \frac{b}{d} \\ H = \frac{m}{r} \end{cases}$$

The Jacobean matrix is:

$$J = \begin{bmatrix} b\text{-}dP & -dH \\ rP & rH\text{-}m \end{bmatrix}$$

$$\text{at } E_1: \qquad J = \begin{bmatrix} b & 0 \\ 0 & -m \end{bmatrix}$$

The eigenvalues are:

$$(b-\lambda)(-m-\lambda) = 0$$
$$\lambda^2 - (b-m)\lambda - bm = 0$$
$$\lambda_1 = b, \lambda_2 = -m$$

Thus, $\Delta x_1 = c_{11} e^{bt} + c_{12} e^{-mt}$
$\Delta x_2 = c_{21} e^{bt} + c_{22} e^{-mt}$

where the c_{ij} depend upon the initial values of Δx_1 *and* Δx_2. Since each function contains a term of the form e^{bt}, an exponential that grows with time, the Δx_i become greater as time increases, and the system diverges from the equilibrium point. Thus, we are concerned with an unstable equilibrium.

At the second equilibrium point, E_2, the following result is obtained:

$$J = \begin{bmatrix} 0 & \frac{-md}{r} \\ \frac{rb}{d} & 0 \end{bmatrix}$$

The eigenvalues are:

$$\lambda^2 + \frac{md}{r} \cdot \frac{rb}{d} = 0$$
$$\lambda^2 + mb = 0$$
$$\lambda_1 = + \sqrt{-mb}$$
$$\lambda_2 = - \sqrt{-mb}$$

This is a different case from any of the previous ones. Since the quantity under the radical is negative, the eigenvalues are complex conjugates and the solution is

$$\Delta x_1 = C_{11} \exp(\sqrt{mb}\, it) + C_{12} \exp(-\sqrt{mb}\, it)$$

$$\Delta x_2 = C_{21} \exp(\sqrt{mb}\, it) + C_{22} \exp(-\sqrt{mb}\, it)$$

where i is the imaginary value $\sqrt{-1}$. By an equation of Euler, complex conjugate exponentials can be reduced to the real functions:

$$\Delta x_1 = c_{11} \sin \sqrt{bm} \quad t + c_{12} \cos \sqrt{bm} \quad t$$
$$\Delta x_2 = c_{21} \sin \sqrt{bm} \quad t + c_{22} \cos \sqrt{bm} \quad t$$

These are oscillating functions and imply that the disturbance neither grows nor decays, but that the system oscillates about the equilibrium point. Thus, we have discovered that there is some neighborhood in which this system demonstrates marginal stability.

In general, the non-linear system will be unstable if any of the eigenvalues of the linearized system has a positive real part, stable if all possess negative real parts, and marginally stable if any (complex conjugate) roots are purely imaginary. The presence of roots with positive real parts can be ascertained from application of Routh-Horwitz criteria to the polynomial equation, eliminating the need to solve the equation for the values of the roots. This and other methods for examining system stability can be found in Ogata *(1967)* and Bowers and Schultheiss *(1958)*.

System Identification by Perturbation

A particularly powerful method for discovering the form of the system model has resulted from the development of linear system theory. Basically, the time response of a linear system to a diagnostic perturbation contains all the information necessary to identify the system model. This is true only for linear systems. However, for many purposes, such as prediction, or even regulation, a linear model will yield sufficient accuracy, and the appropriate linear model (for some operating range) can be constructed in this way.

There are three diagnostic perturbations: the impulse, step, and sine functions. The second is the most appropriate for biological population systems and consists of an abrupt change in the level of a system variable. The behavior of the system subsequent to this abrupt change is examined, and from the graphical or numerical results the values of exponents and constants can be calculated. These imply certain relationships among the basic variables and define these relationships uniquely in a differential equation model. An example of a step function in a predator-prey system would consist of an abrupt addition of a given

number of either organism. A negative step could also be employed, such as the removal of some of the predators in a plant-herbivore-predator system.

There is a large number of other diagnostic methods for model identification that derive from systems theory—many of which have not yet been employed in biological investigation. A particularly interesting introduction to the subject is contained in Milsum *(1966)*.

Conclusion

The intent of this paper has been to provide a brief introduction to constructing and solving dynamic population models. Some examples have been presented to illustrate the basic approach. A great deal has been left out. No mention has been made of stochastic elements in such models, nor has anything been said about the utilization of the models for pragmatic purposes. Emphasis has been placed on how the model reveals the structure of the system, which will be the principal aim of many investigators. Those of us who are interested in resource management and optimization of yield, or the subsidiary problem of minimization of damage, need system models for this purpose. Given good population system models, we can explore in a meaningful way modification of the destructive effects of the pest, or devise an optimum strategy to obtain yields in spite of its effects. This is another topic, requiring for its solution models of a different organizational system, but which is no different in concept from the problems discussed above. The point that needs general recognition from population dynamicists is that it is both necessary and relatively easy to approach their systems from a dynamic point of view.

Literature Cited

Bower, J. L. and P. M. Schultheiss.
1958. Introduction to the design of servomechanisms. 510 pp. New York: John Wiley and Sons, Inc.

Holling, C. S.
1966. The functional response of invertebrate predators to prey density. Entomol. Soc. Canada Mem. 48: 1-86.

Milsum, John H.
1966. Biological control systems analysis. 466 pp. New York: McGraw Hill.

Ogata, K.
1967. State space analysis of control systems. 596 pp. New York: Prentice-Hall, Inc.

Watt, K. E. F.
1959. A mathematical model for the effect of densities of attacked and attacking species on the number attack. Canad. Entomol. 91: 129-144.

Watt, K. E. F.
1960. The effect of population density on fecundity in insects. Canad. Entomol. 92.

MODELING FOREST INSECT POPULATIONS— THE STOCHASTIC APPROACH

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ORDINARILY, phenomena such as growth of a population or changes in the qualitative character of a population are not open to immediate observation in all their details. Usually we observe only a few external manifestations of the phenomenon, i.e. the inputs and outputs of a black box.

When we view a complex phenomenon—complex in the sense that we do not fully understand what is occurring—we attempt to explain it by using mechanisms that, through experience or imagination, appear simple or elementary. These simple mechanisms we use to explain a phenomenon are sometimes, perhaps often, only apparently simple.

This paper is not a review of probability theory nor an advocation for the general use of probability techniques by entomologists. Rather, it is an attempt to demonstrate the utility and the power of probabilistic models. Probabilistic and deterministic models will be contrasted to illustrate the fundamental differences between the two types of mathematical models. The level and tone of the presentation is a compromise between a desire for some mathematical sophistication and a realization that such sophistication would completely negate the utility of this paper as an introduction for the non-mathematically inclined.

A model may be defined as a set of hypotheses representing a class of phenomena as a particular combination of elementary mechanisms. Thus, a model is a hypothetical structure composed of elementary mechanisms joined by a set of hypothesized relationships.

The introduction of mathematics into the modeling process represents a logical step in the evolution of a science. Mathemati-

cal models have assumed some acceptance because: (1) the symbols are easily manipulated; (2) definition is precise i.e., lack of ambiguity; and (3) subjective judgment is reduced in the evaluation of the hypothesized relationship. In the remainder of the paper, a model will always refer to a mathematical model.

The elementary mechanisms that we invoke in building the structure of the model may be deterministic or probabilistic. A model is deterministic if a particular mechanism implies that every variable in the system is a function of the others.

For example, consider Thompson's *(1922)* model for a parasite-host system. The fraction of the host population attacked by the t^{th} generation is

$$f = \frac{p R^t}{h - p \frac{(R^t - R)}{(R-1)}}$$

where

f = fraction of host population attacked by the t^{th} generation.
p = number of parasites initially present $t = 0$.
h = number of hosts initially present $t = 0$.
t = generation.
R = ratio of reproductive power of parasite to host.

Knowing any four of the five parameters of the model we can solve for the fifth. The model states that beginning with the same number of hosts, h, parasite, p, and ratio of reproductive power R at the t^{th} generation we will always have the same fraction f of host population parasitized.

If at least one variable is a chance or random variable then the model is probabilistic. For example, consider a stationary population subject to chance immigration. The immigrants after arriving remain in the population. The number of individuals in the population at time t is given by

$$N_t = N_o + I_t$$

where

N_o = number of individuals in the population initially, $t = 0$.
I_t = number of individuals who have immigrated at or before time t.

N_t = number of individuals in the population at time t.

The number of individuals in the population at time t is a random variable because the number of immigrants at or before time t is subject to chance variation. The term random implies that the process under consideration (immigration) is in some sense probabilistic.

In the last 50 years deterministic models have been developed for a wide variety of biological phenomena. The increasing development of probabilistic models in the past twenty years is due to the failure of deterministic models to provide a description of all the phenomena one may wish to study. Deterministic models fail to take into account the role of chance fluctuations in the development of the process. For example, the competition experiments of Park *(1948)* with flour beetles showed that under a given set of initial conditions the same species did not always survive.

The main appeal of deterministic models appears to lie in their relative mathematical simplicity not in their philosophical foundation. Any debate between the advocates of deterministic and probabilistic models revolves around the economics of model construction and analysis, not on the theoretical applicability of the stochastic model. The advocates of deterministic models find some support for their position in the fact that *sometimes* when a population is large, a description of the deterministic type is equal to the expected value of the probabilistic model.

Both deterministic and stochastic models must satisfy Neyman's *(1960)* criteria of "broad applicability" and "identifiability of details". Broad applicability refers to "the possibility of deducing from the model verifiable consequences relating to categories of observation other than those for which the model was constructed." Identifiability of details refers to identifying in the empirical world elements that correspond to hypothetical entities in the model.

The subsequent comparison of probabilistic and deterministic models closely follows a discussion by Lucas *(1964)*.

A probabilistic model is defined by the relation

$$P_R[Y \leq y] = (\underset{\sim}{\psi}, \underset{\sim}{X}; \underset{\sim}{y})$$

where

Y is a random variable and

F is a probability distribution with arguments y and column vector parameters ψ and X

$\underset{\sim}{\psi}$ is a vector that is invariant over a class k of situations

$\underset{\sim}{X}$ is a vector that varies over the class k.

For example, consider the familiar normal linear regression model

$$f(y, \alpha, \beta, \sigma^2, x) = \frac{1}{\sqrt{2\pi\sigma^2}} \left[\exp - \left(y - \alpha - Bx\right)^2 \Big/ 2\sigma^2\right]$$

$$P_R[Y \leq y] = \int_{-\infty}^{y} f(y, \alpha, \beta, \sigma^2, x)\, dy$$

where $f(y, \alpha, \beta, \sigma^2, x)$ is the probability that the random variable Y assumes a value y.

It will be assumed that the probabilistic elements are written in the form

$$Y = \Delta(\underset{\sim}{\psi}, \underset{\sim}{x}) + \varepsilon$$

The subscript tilde $\sim$ denotes a column vector. Thus $\underset{\sim}{X}$ is a column vector $[x_1, x_2, \ldots x_n]$ having n elements.

The random variable $\underset{\sim}{X}$ will be treated as an input or independent variable and y will be considered as an output or dependent variable.

$$\Delta(\psi, X) = \int_{-\infty}^{\infty} y\, dy\, F(\underset{\sim}{\psi}, \underset{\sim}{X}, y)$$
$$= E(y \mid \underset{\sim}{\psi}, \underset{\sim}{X})$$

This is the expected value or mean of the random variable.

The probability distribution of ε, the deviation from the expected value, is given by

$$P_R(\varepsilon \leq e) = F(\underset{\sim}{\psi}, \underset{\sim}{X}, e + \Delta(\underset{\sim}{\psi}, \underset{\sim}{X}))$$

where $e = y - \Delta(\underset{\sim}{\psi}, \underset{\sim}{X})$.

The expected value of the deviation is zero.

$$E(\varepsilon|\psi, X) = E(y\text{-}\Delta(\underset{\sim}{\psi}, \underset{\sim}{X}) \mid \underset{\sim}{\psi}, \underset{\sim}{X})$$
$$= E(y|\underset{\sim}{\psi}, \underset{\sim}{X})\text{-}\Delta(\underset{\sim}{\psi}, \underset{\sim}{X})$$
$$= 0$$

The probabilistic model has deterministic aspects, the form of the probability distribution and the values taken on by ψ and X.

Consider a deterministic model, i.e. a model with no chance mechanism, of the form

$$\gamma = \Delta^*(\underset{\sim}{\varphi}^* \underset{\sim}{X})$$

where γ corresponds to the expected value of the output variable y.

Because real data never follow γ exactly an additional term ε^* is needed to account for the deviations from the model. The model becomes

$$y = \gamma + \varepsilon^* = \Delta^*(\underset{\sim}{\psi}^* \underset{\sim}{X}) + \varepsilon^*$$

In order to make a probability statement about the deviation, it is assumed that ε^* follows some cumulative density function

$$P_R[\varepsilon^* \leq e^*] = F^*(\underset{\sim}{\beta}, \underset{\sim}{X}, y)$$

where β is a column vector of parameters invariant over the class of situations. The column vector of parameters β is used instead of ψ because often very simple assumptions are made about F*. For convenience ε^* is often assumed to follow a normal distribution or some other well tabled distribution. The assumption that

$$E(\varepsilon^* | \underset{\sim}{\beta}, \underset{\sim}{X}) = 0$$

is not always justified. For example, consider the use of the deterministic model

$$y = X_1\beta_1 + \varepsilon^*$$

when the "true" model is in fact

$$y = X_1\beta_1 + X_2\beta_2 + \varepsilon$$

The deviation ε^* is obviously equal to $\chi_2\ \beta_2 + \varepsilon$ and its expected value is

$$E(\varepsilon^* | \beta_1, X_1) = X_2\beta_2$$

not zero unless $\beta_2 = 0$.

Although Δ^* and ψ^* may have the same form as Δ and ψ this is not always so. In the deterministic Lotka-Volterra equations the derivatives of the first moments are functions of products of means. In the stochastic analogy developed by Chiang *(1954)* the derivatives of the first moments are functions of means of products.

The difference between the two types of models revolves around the role of the probabilistic element in the model. In the

stochastic model the probabilistic element is an integral part of the model. In the deterministic model the probabilistic element is added because of the nature of the real world. It is not mandatory to attach a probabilistic interpretation to the deviations. There is nothing to prevent a researcher from using the sum of squared deviations from the model or any other statistic to classify a model as good, bad, or indifferent. Intuitively we are inclined to say a model with a small sum of squared deviations is better than a model with a larger sum of squared deviations. But how much better? The probabilistic interpretation of the deviations is an attempt to say how much better under the assumptions of F*, the cumulative density function assumed for ε^*.

For any given deterministic model it is generally possible to construct a variety of stochastic analogs. For example, the deterministic logistic does not distinguish between the situation where the intrinsic rate of increase represents purely reproductive growth and the situation where the intrinsic rate of increase represents a net balance between births and deaths.

If the intrinsic rate of increase represents a purely reproductive growth, a modified pure birth process[1] may be used as a stochastic analog of the deterministic model. When the intrinsic rate of increase represents a net balance between births and deaths a modified birth-death process[2] may be used as a stochastic analog.

In the preceding paragraph, two stochastic processes were introduced. A stochastic process may be defined as a process that may occur in the real world that has some probabilistic element involved in its structure. The phrase conventionally refers not

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[1] A pure birth process is a stochastic process in which it is assumed that each individual in the population acts independently and is subject to a birth rate λ. It is assumed that there is no death, no migration, and the population and the environment are homogeneous. In the pure birth process the number of births in a population of size $N(t)$ at time t is assumed to be $N(t)\ \lambda$. In the modified pure birth process the number of births in the population at time t is $\lambda N(t)\ (K-N(t))$, where K is the carrying capacity of the environment.

As the population approaches the carrying capacity, the birth rate declines.

[2] A simple birth-death process assumes that a population composed of homogeneous individuals acting independently is subject to a birth rate λ and a death rate λ. The modified birth-death process assumes that the population fluctuates between two limits N_1 and N_2, $N_1 < N_2$, where N_2 corresponds to the saturation level. As the population approaches N_2 the death rate increases and the birth rate decreases. The reverse is true, as the population approaches N_1.

only to the actual process but also to its mathematical representation. The simple birth process and the birth-death process are examples of an important class of stochastic processes known as Markov processes. A Markov process is a process with the property that knowing the state of the system at time t, knowledge of its past behavior does not alter the probability of any particular future state.

Although many, if not most, biological processes are non-Markovian the Markov assumption serves as a useful approximation in many instances. Markov-type assumptions are inherent in the construction and analysis of many deterministic models, such as

$$S=P_1P_2P_3 \ldots P_i$$

where

S = generation survival

P_i = survival rate in the i^{th} stage.

Curent analyses of models of this type treat survival in the i^{th} stage as a function only of the number entering the stage and mortality forces acting in this stage. This type of analysis ignores the influence of past behavior or experience on survival in the i^{th} stage.

The difference between probabilistic and deterministic models sometimes becomes apparent when one considers the ultimate extinction of the population. In the simple birth-death model with birth rate λ and the death rate μ the probability of ultimate extinction is

$$\lim_{T \to \infty} P_R \left[X(t) = 0 \mid N_{(o)} \neq 0\right] = \begin{matrix} 1 \text{ if } \lambda \leq \mu \\ 0 \text{ if } \lambda > \mu \end{matrix}$$

where

$N(o)$=the number of individuals in the population at time zero

$X(t)$ = the number of individuals in the population at time t.

If birth rate is less than the death rate, extinction is expected. It is surprising, however, that when the two vital rates are equal, extinction is also certain.[3] Although extinction is certain when

[3] A mathematical proof of this phenomenon may be obtained by considering the gambler's ruin problem. (*Feller 1957*)

the vital rates are equal, the expected ultimate population size is N(0). This apparent anomaly occurs because although a few populations will rise to very high values, most populations will be extinguished at very low values so that a constant mean is achieved. Bailey *(1964)* comments that this result indicates that fallacy of attaching too much attention to stochastic mean values even when they exactly equal the corresponding deterministic quantities.

A population in which the intrinsic rate of increase represents a net balance of births and deaths may approach the saturation level K, by (1) increasing the mortality and preserving a constant mortality, or (2) decreasing fertility and maintaining a constant mortality, or (3) by some combination of (1) and (2). Therefore, the approach toward the saturation level may be represented by a variety of models.

Leslie *(1958)* investigated the two extreme situations for populations with stable age structures. He concluded that the imposition of a force of mortality independent of the age distribution, when fertility remains constant and mortality is a linear function of the number present at time t, will result in sigmoid population growth. If the initial population is not *stable* there may be considerable departures from the logistic, although population growth will still follow a sigmoid form. The age structure models Leslie studied show dampened oscillations. Bartlett *(1957)* pointed out that under certain conditions the modified stochastic birth-death process continued to show undampened fluctuations with an amplitude depending on the population size. Feller *(1939)* showed that in the stochastic version of the logistic, fluctuations have in the main the effect of diminishing the rate of population growth.

The subsequent paragraphs are devoted to the development of stochastic models for populations subject only to the risk of death. The first model illustrates the theoretical assumptions and the methodology of model construction. An example of the applicability of the stochastic model to a particular entomological phenomenon is shown. The problem of competing risks is briefly considered.

Assume that a homogeneous isolated population is subject only to the risk of death. At time $t = 0$ the population is composed of $N(0)$ individuals. Each individual acts independently and is subject to the same risk of death. the probability of death of an individual in the interval $(t, t + \Delta t)$ is

P_R (death in the interval $(t, t + \Delta t)$ | alive at t) $= \gamma_t \Delta_t + 0(t)$

where γt is the force of mortality, i.e. instantaneous death rate.

The probability of being alive at time $t + \Delta t$ is given by

$$P_R(t + \Delta t) = P_R(t) \cdot (1 - \gamma_t \Delta_t + 0(\Delta_t))$$

where

$P_R(t)$ = the probability of being alive at time t

$1 - \gamma_t \Delta_t + 0(\Delta_t)$ = the probability of surviving the interval $(t, t + \Delta_t)$

After some mathematical manipulations, which may be found in any elementary text on stochastic processes (for example *Parzon 1962*), we obtain

$$P_{R(t)} = \exp(-\int_0^t \gamma_t d_t)$$

as the probability of survival to time t.

The average or expected number of individuals alive at time t is

$$E(N(t)) = N(0) \cdot P_r(t)$$

$$= N(0) \cdot \exp(-\int_0^t \gamma_t d_t)$$

If the force of mortality is constant the expected number of individuals alive at time t is $N(0) \cdot \exp(-\gamma t)$.

Utilizing the assumptions that each member of the population acts independently and is subject to the same force of mortality γ_t we obtain

$$P_R\left[\begin{array}{l|l} N(o) - k \text{ individuals alive at time } t & N(o) \text{ alive at time } t = 0 \end{array}\right] = \binom{N(o)}{N(o)\text{-}K} P_R(t)^{(N(o)\text{-}K)} \cdot (1\text{-}P_R(t))^{K}$$

as the probability at time t exactly $(N(0) - K)$ individuals will be alive. The form of this equation is recognizable as the binominal probability law.

Let us now consider the hunger component of the predation model of Holling *(1966)* as a real life phenomenon.

$$H = HK(1\text{-}\exp(-AD \cdot TF))$$

where

H =hunger level in grams of food to satiate an insect at any given time.

HK=maximum capacity of the gut.

AD=rate of digestion.

TF =time without food from complete satiation.

This model can be used to show the applicability of the probabilistic approach. For simplicity I have reformulated the model in terms of food remaining in the gut,

$$\begin{aligned} R &= HK - H \\ &= HK \cdot \exp[-(AD \cdot TF)] \end{aligned}$$

The revised model can be recognized as the expected number of units remaining in a population subject to a constant rate of decrease, AD. The probabilistic formulation of Holling's model not only provides the probabilities of occurence but also indicates the assumptions that are implicit in the model.

Let us now assume that an isolated homogeneous population is subject to risk of death by three mortality factors R_1, R_2 and R_3.[4] The factors are assumed to be acting contemporaneously on the entire population. Associated with each factor R_i is a force of mortality $\gamma_{\tau i}$. The sum of the individual forces of mortality $\gamma_{\tau i}$ is μ_τ, the total force of mortality.

In the interval $(t, t + \tau)$ the ratio

$$\frac{\gamma_{\tau i}}{\mu_\tau} = r_{ti}$$

is independent of time τ but is a function of the interval and the mortality factor R_i. Therefore, the absolute magnitude of cause-specific mortality may vary at any instant subject only to the restriction that it remain a constant proportion of the total force of mortality μ_t throughout the interval $(t, t + \tau)$.

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[4] The model for competing risk was developed by C. L. Chiang (1960): Fourth Berkeley Symposium on Mathematical Statistics and Probability, Vol. 4: 413 pp. Univ. of California Press. 1961.

Occasionally, we may be interested in the influence of a single mortality factor upon a population in the absence of competing risks—for example, how many individuals would be killed if a predator were the only mortality factor operating. Except under very special circumstances, this information is not available from field records. Commonly we observe mortality in populations subject to a multitude of mortality factors. If we wish to determine the mortality associated with a specific factor operating in the absence of other causes of mortality, we must build some theoretical relationship between the crude *probability of death* from factor i operating in the presence of other factors and the *net probability of death* from factor i operating in the absence of other mortality factors.

The simple death process discussed in the previous paragraphs is used to develop a theoretical relationship utilizing the assumptions that forces of mortality are additive and that within the interval $(t, t + \tau)$ the ratio $\frac{\gamma_{\tau i}}{\mu_\tau}$ is constant.

The crude probability of death from factor i in the interval $(t, t + 1)$ is

$$Q_{ti} = \int_t^{t+1} [\exp -(\int_t^{\tau} \mu_t dt)] \gamma_{\tau i} d\tau$$

where $\exp\left(-\int_t^{\tau} \mu_t d_t\right)$ is the probability of survival from t to τ, and $\gamma_{\tau i}\, d\tau$ is the instantaneous probability of death from factor i at time τ.

The net probability of death from factor i in the interval $(t, t + 1)$ when it is the only factor operating is

$$q_{ti} = 1 - \exp\ [-\int_t^{t+1} \gamma_{\tau i} d\tau]$$

If the assumption of a constant relative risk is introduced we obtain

$$Q_{ti} = \frac{\gamma_{\tau i}}{\mu_\tau} \int_t^{t+1} [\exp - \int_t^{\tau} \mu_t\, d_t] \mu_r dr$$

$$= \frac{\gamma_{\tau i}}{\mu_\tau} q_t$$

as the relationship between the crude probability of death from factor i in the interval $(t, t-1)$, the forces of mortality γ_{ti} and μ_t and the probability of death in the interval q_t. The probability of death in the interval is of course equal to the sum of the crude probabilities of death.

The relationship between the net and crude probability of death from factor i under the *assumptions of the model* can now be obtained:

$$q_{ti} = 1 - \exp\left[- \frac{\gamma_{\tau i}}{\mu_\tau} \int_{t}^{t+1} \mu_t dt \right]$$

$$(Q_{ti}/q_t)$$

$$= 1 - P_t$$

Although the assumptions of the model for competing risks may be unrealistic for many populations, the model shows what assumptions are made and how they are used to build the desired relationship. The next step in the model building process is testing the adequacy of the model.

This particular model was selected for review because it has some relevance to life table construction and mortality models currently employed in entomology.

Population dynamics, models, and systems analysis are the magic words of quantitative forest entomology today. The success of model building and system analysis depends on the extent and organization of entomological kowledge. Elaborate mystical arrays of symbols are no substitute for carefully planned field and laboratory studies. Modeling should not only indicate possible mechanisms but also should indicate where additional biological knowledge is needed.

In this paper I have ignored the empirical models developed by massive data screening programs because although they may lead to good predictions, they are often difficult or dangerous to interpret in terms of underlying biological mechanisms. Screening and correlation programs are useful as fishing trips to locate interesting areas for further study. All too often such programs force the researcher to perform mental contortions to explain his observed relations in terms of a biological phenomenon. Philo-

sophically such an approach to model building is repugnant because it tends to nourish the belief that given sufficient data in large enough quantities a computer can and will find the correct relationship. Access to an electronic computer is not a substitute for careful analytical thinking by the entomologist and statistician.

Simple models like the logistic have been very useful in biology because the parameters are often rather insensitive to small changes. The parameters represent a kind of average value or balance. The parameters are a function of the intrinsic and extrinsic factors associated with the population. Although simple models are intuitively appealing, the interpretation of their parameters must be done with care.

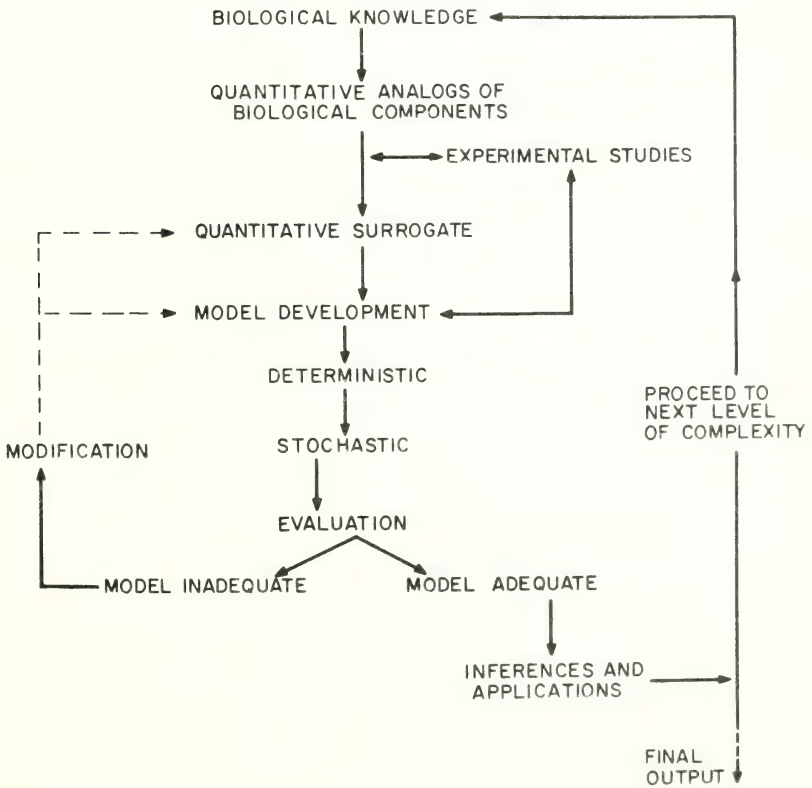

Figure 1.—Schematic diagram of model-building strategy.

Stochastic and deterministic models were compared to show the difference in their philosophical approach to modeling. The distinction between stochastic and deterministic models has been somewhat blurred because sometimes the expected value of the stochastic model is equal to the value of the deterministic model. But this is not always true. Is the entomologist interested in average behavior? Population explosions and extinction may be of greater interest than average behavior. Stochastic models with their embedded chance mechanisms appear to be more adequately suited to the study of such biological phenomena than the more classical deterministic models.

Because stochastic models often involve a more complex mathematical formulation, the economics of model construction and analysis must be evaluated in terms of future benefits. After it has been decided that the population dynamics of an insect are to be studied, the researcher must develop a strategy for model construction and analysis. Figure 1 illustrates a stepwise strategy that might be used for model development in forest insect population dynamics.

The relative mathematical simplicity of deterministic models is used to obtain an idea of the form of the interrelations of the variables. In the strategy diagrammed in figure 1, deterministic and stochastic models for restricted situations are initially developed for restricted situations. The restrictions are gradually relaxed to obtain models for more general situations. For example, initial lack of knowledge of the mode of action of predators and parasites will necessitate the use of crude submodels until sufficient information is available to build more realistic models.

Successful model building demands complete cooperation of entomologist and statistician. The entomologist supplies the biological knowledge about modes of action and interrelationships. The statistician uses the biological information to form a mathematical structure.

Empirical (predictive) models and rational (mechanistic) models, both deterministic and stochastic, are essential to the development of good population models. The complex interre-

lationships that we wish to understand require not only the mathematical and statistical ability of the statistician but also the genius of the biologist to design the studies needed to gain deeper insights into biological phenomena.

Literature Cited

Bailey, N. T. J.
1964. The elements of stochastic processes with applications to the natural sciences. 249 pp. John Wiley & Sons, New York.

Bartlett, M. S.
1957. On theoretical models for competitive and predatory biological systems. Biometrika 44: 27-42.

Chiang, C. L.
1954. Competition and other interactions between species. *In* Statistics and Mathematics in Biology. Ed. O. Kempthorne. pp. 197-215. Univ. Iowa Press.

Feller, W.
1939. Die grundlagen der voterrasihen theorie des kamptes ums dasein in wahrscheinlichketis theoretischer behandlung. Acta. Biotheoret. A (Leiden) 5: 11-40.

Feller, W.
1939. An introduction to probability theory and its applications. Ed. 2. Vol. 1, 461 pp. 1957. John Wiley & Sons, New York.

Holling, C. S.
1966. The functional response of invertebrate predators to prey density. Ent. Soc. Canada Mem. 48, 86 pp.

Leslie, P. H.
1958. A stochastic model for studying the properties of certain biological systems by numerical methods. Biometrika 45: 16-31.

Lucas, H. L.
1964. 'Stochastic elements' in biological models, their sources and significance. *In* Stochastic Models in Medicine and Biology, Ed. J. Gurland. 393 pp. Univ. Wisc. Press.

Neyman, J.
1960. Indeterminism in science and new demands on statisticians. J. Amer. Stat. Ass. 55:625-639.

Neyman, J. and E. L. Scott.
1959. Stochastic models of populations dynamics. Sci. 130:303-308.

Park, T.
1948. Experimental studies of interspecies competition. I. competition between populations of the flour beetles, *Tribolium confusum* duval and *Tribolium castaneum* herbst. Ecol. Monogr. 18:265-308.

Parzon. E.
1962. Stochastic processes. 323 pp. Hollen-Day, Inc.

Thompson, W. R.
1922. Theorie de l'action des parasites entomophages. Les formules mathematiques du parasitisme cyclique. Compt. Rend. 174:1201-1204.

SOME PRACTICAL FIELD PROBLEMS ASSOCIATED WITH SAMPLING OF SCARCE INSECTS

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IT IS WELL for us now to review some sampling problems that we must face in gathering adequate field data for quantitative analysis. I've never seen a plan of research that wasn't changed to some extent once the field work commenced. Many plans are changed drastically because the conditions in the field just do not always provide the expected. This is why we enjoy working with field biology problems, perhaps. I shall not attempt to discuss all of the many practical field problems that we face. If insect population models are to be realistic, however, the problems of sampling the natural populations must be resolved to some extent. The sampling of scarce populations is particularly vexing. We are often faced with budget and manpower limitations, and we have difficulty in obtaining the statistical precision we desire.

We should make a real distinction between sampling for population dynamics research purposes and sampling for trend prediction in surveys. The requirements for the two are completely different. In the first we are attempting to define the real causes of population fluctuations. This perhaps will lead to more effective control procedures either by direct or indirect means. When sampling for trend prediction, we are involved more directly in applied forestry. Here we want to answer the related questions—is this population going to increase or decrease and will significant damage occur? I believe that often there is a tendency to mix the two approaches. Methods of trend prediction are generally developed from population research data, but in application these methods will differ somewhat from those carried out in population research. Survey evaluation procedures must be relatively

simple, inexpensive to apply, and fast. It is obvious that they must also give reliable answers.

Before considering some specific examples pertaining to survey evaluations and sampling of scarce insects, it might be well to comment briefly on what I like to call "nonsense" statistics. Some research workers become so wrapped up with the idea that everything must be expressed in statistical terms that they fail to use common sense. One good example, and a simple one, is concerned with the analysis of variance. How often have you seen a complete analysis made for a comparison of two obviously different things? One should not waste his time making an analysis if the differences are so striking that he knows the results before he even starts the computations. A second type of "nonsense" statistic is as commonly seen and is much more serious. I'm afraid the computer has added to this problem; some biologists act as though they do not need to think if a computer is used to analyze their data. I refer here to the computation of correlations. Lots of things correlate. For example, in our climate the number of letters in the spelling of the months would correlate with mean monthly temperature. Most of the colder months have long spellings, the warmer months short spellings. We can compute such a correlation but all we end up with is nonsense. Why compute a correlation or talk about it if it has no relevance or usefulness? All too often the computer hands us correlations which are mathematically correct but are biologically meaningless. If a correlation cannot be defended on the basis of logic and biological common-sense then it probably is nonsense. When correlations are published they should be defended by sound biological reasoning. The computer only answers "yes" or "no" to a question. It is up to us to do the creative part of the research; we must answer the question "why?"

I am going back a few years in my own research to briefly comment on population research in contrast to research on evaluation methods. I know that all of you are familiar with sequential sampling, and most of you are aware that sequential sampling procedures were developed nearly 10 years ago for the Black Hills beetle, *Dendroctonus ponderosae*. You may not be aware of the

objectives of the research that preceded the development of the method for this insect. The major objective of the research at that time was to develop an evaluation system for Black Hills beetle infestations. We were interested primarily in obtaining a practical method for measuring trends. Secondarily, we hoped to obtain a considerable amount of information on the population dynamics of the Black Hills beetle. We did not pin down the major causes of population fluctuations; we did not even identify many of them. We did develop a workable sequential sampling method for evaluating trends. I had hoped the work would continue on the evaluation method because it does need refinement. However, more of the work since that time has been on population dynamics rather than evaluation procedures.

Sequential sampling is one of the better procedures to use in predicting trends in populations. However, it is not a part of population dynamics research. It may be a product of such research but has very little usefulness in the research itself.

Now, to the main point, there are many problems associated with sampling of scarce insects.

Measurement of population numbers.—Often we hear comments on this problem, such as, "I sampled all plots in the usual fashion and counted no budworms, but I saw an occasional one on other branches" or "Between the two outbreaks of the southern pine beetle I never saw a beetle in the entire region." The problem is simply presented. How can we give statistics on populations without numbers? Granted, a greater amount of sampling would eventually give us quantitative data, but usually we are limited by the time and manpower available.

Identification of mortality factors.—When we do have a population that is measurable, we often try to evaluate the effects of mortality factors. By a great effort, perhaps, we collect 30 larvae and we find that 12 or 40 percent of them are parasitized. Statistically it is correct, and it fills in a slot in the life table. However, any biologist who considered that value for parasitism a valid one would be dreaming. A second collection of 20 larvae might be 90 percent parasitized. Which is correct for the population? The answer is neither one; we just cannot get precise measurements of

population reductions with such meager samples. Then, if we add to this the need for separation of mortality factors, perhaps eight or ten parasite species, we are indeed on shaky ground.

Destruction of population by sampling.—When populations become scarce they are not spatially distributed in the same fashion for all species. This is not a very profound statement because the same is true for outbreak populations. However, the differences may be much more striking among scarce insects. Some of them, such as bark beetles, are fantastically clumped. One Black Hills beetle infested tree in two sections of land is not uncommon. The individual infested tree often contains as many beetles as the average tree in an outbreak situation. Thus, the insects present are confined to micro-portions of their total habitat. These favorable locations may not be unique; there may be many other favorable niches not occupied in the surrounding forests.

Knowing our populations, we are sometimes able to locate clumps of plentiful insects; but if we concentrate our sampling on these clumps, we cause a real change in that population. Our destructive sampling procedures may be the major mortality factor affecting that population! When populations are large we can assume that our sampling has no affect on the population but this is not so with scarce populations.

The foregoing are three of the real problems we face when attempting to sample scarce insects. What can we do? One fact is apparent, we just will not produce the comparative quantitative data that our analyses ask for. We are usually day-dreaming if we think we can. Yet we are working on a key part of the population dynamics problem and we need reliable information.

I believe the answer to the problem is to take a completely different approach. This approach is not entirely satisfactory to those who insist upon exact data that can be subjected to mathematical analysis. The approach also requires a patient and very talented research man. I am referring to direct careful observations followed by thorough subjective analyses based on a limited amount of actual data.

In some ways we have gone too far in our enthusiasm for exact quantitative data to support all statements. Some field

research workers do not know how to make observations, they just never have done this kind of work. Many even feel guilty if they sit in one spot and record nothing for fifteen minutes. The researcher must spend hours observing and recording what he sees, especially when studying scarce insects. When he has completed his work and reports his results those results must be accepted as reliable. He should not be given the thumbs down comment, "Where are your data to prove it." That question is often the greatest deterrent to creative work that can be expressed. I don't advocate complete acceptance of every unsupported belief of the researcher by any means, but conclusions based on long hours of close observation are not just unsupported statements. In most cases quantitative data will be recorded but often not enough for the statistical precision desired. It is the responsibility of the research worker to point out clearly that he is working with sparse populations and must rely on subjective analyses. Then the reviewer should respect the judgment of the researcher (provided the work has been truly thorough).

Jack pine budworm research.—To illustrate the preceding comments on the usefulness of observations, we will briefly consider two projects. The first concerns studies on the jack pine budworm, *Choristoneura pinus*. In this project there were ample budworms for population measurement, but problems developed when we attempted to analyze predation by birds. In particular, we found it possible to get quantitative information on the resident birds. but impossible to assess the effect of non-resident individuals. We found by observation and some measurements that non-resident birds were consuming large quantities of budworms. These birds were mainly blackbirds, including the red-winged blackbirds, Brewer's blackbird and the cowbird. In one area a flock of 700 to 1,000 of these birds was feeding on budworms during the late larval and pupal stages. If normal sampling with minimal time for observation had been maintained, we possibly would not have noticed their activity. These birds were the major factor controlling populations of the budworm in the one area. This area was a special one in that the jack pine site was only about 600 acres in extent and was surrounded by lowlying areas where many

blackbirds were nesting. Nevertheless, the findings illustrate the point that observational data are vital to research.

Saperda inornata and Oberea schaumii.—The second project concerns two insects which are apparently scarce at all times. They also occupy the same ecological niche but exist at such low levels in nature that they never seem to compete. Both are regulated at low levels by factors other than food availability. These insects infest aspen twigs or suckers in diameters ranging from 1/4 to 3/4 inch. Larvae of both insects bore in the twigs. Adults can be found from June until August, although the emergence period of both is completed in June. Their life cycles in the twigs differ. *Saperda inornata* develops in 1 or 2 years while *Oberea schaumii* requires 3 years from egg laying to adult emergence.

Our data on suckers infested illustrate the scarcity of the insects. These data on six areas involve careful inspection of 13,500 suckers each year; 2,250 in each area each year. Egg niche construction data are presented in table 1. The data for *Saperda inornata* are in terms of galls because this insect may lay more than one egg at a location. Biologically a gall in *Saperda* is equivalent to an egg niche in *Oberea* because it is rare for more than one adult to emerge from a single gall.

These data when carefully analyzed illustrate our need for

Table 1.—Number of egg niches or galls constructed by Oberea schaumii and Saperda inornata on aspen suckers, 1964 to 1966

Area	Egg Niches of *Oberea*			Galls of *Saperda*		
	1964[1]	1965	1966	1964	1965	1966
1	34	12	158	2	24	63
2	308	159	390	22	73	73
3	163	146	212	38	50	122
4	92	50	230	37	24	100
5	—	33	148	—	18	102
6	—	55	262	—	12	81

[1] In 1964 only 4 areas with 1,500 suckers in each were surveyed. The number was increased to 6 in 1965 and the sample was increased to 2,250 suckers in each area.

observation. In 1964 the amount of egg production was very low among the *Saperda* adults. The reason might have been apparent two years prior. We found it extremely difficult to find emerging *Saperda* adults in the spring of 1964. *Oberea* adults on the other hand were as common as in 1965 and 1966.

In 1965 we increased the sample size (1,500 to 2,250 suckers) and added two areas (5 and 6). Our counts dropped in the *Oberea* record but increased significantly in the *Saperda* record. Why? The emergence of adults of *Oberea* was as large as in 1964 and *Saperda* adults were much more common. They seemed as common as for both species in 1966. The answer to the question was revealed in our rearing studies in the field. The weather in 1965 was adverse. On two June dates in 1965 temperatures overnight reached lows below 25°F. About half of the adults died in our cages. Daytime temperatures through much of June and July were below normal.

In 1966, egg production of both species was high. Again weather was responsible. We had warm temperatures and very little rain throughout the egg laying period.

Only one life table has been completed for the tagged niches. The *Saperda* galls tagged in 1964 were removed after emergence was complete in June 1966. One *Saperda* adult emerged. This was certainly a small number on which to base many conclusions. Our data for the remainder of the study involves larger numbers but we know that emergence numbers will not be large. Therefore, we must rely on much observational information, with some quantitative data to support our conclusions.

I have not attempted here to describe procedures for studying populations of scarce insects. You are all well aware that different techniques are required in handling each problem encountered. We must study such insects and should not give up when the problems seem insurmountable.

We must keep our perspective in population dynamics research. We may enjoy studying insects but just the study of insects is not enough because our primary aim must be to produce healthy forests with a minimum of damage by insects. Population dynamics models must take in account the condition of the host tree

which is often the most important factor involved. I am very suspicious of models which revolve around the insect, its parasites and predators, and climatic factors associated with changes in numbers. The two most important variables are the insect and the host. We must thoroughly understand the ecology of both if we are to solve the complex population problems ahead of us.

Finally, let's be critical of our own work but at the same time be willing and eager to accept new ideas and approaches suggested by others. Above all, we must take a few minutes each day to sit on that stump and observe what is happening.

QUALITY CONTROL IN ENTOMOLOGICAL SAMPLING

(Abstract)

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THE USEFULNESS of any sampling program depends upon (1) a clear idea of the question to be answered, (2) a consideration of the various elements which enter into effective sampling, and (3) a means of analyzing the data when collected.

The necessity of phrasing the right question seems so elementary when you see it written out, but it is the heart of the matter of getting started. The kind of question asked is the difference between the EXPERIMENTAL approach and the ANALYTICAL approach. Unfortunately, we are often embarked on an analytical mission equipped with only experimental tools.

The point of all population sampling, brood mortality measurement, population trend estimation, etc., should be to reach a decision about some hypothesis, or at least to frame one. We sample because we want to answer some question. The sessions which preceded this one presented many questions. When these are asked about field situations, they are answered by making sample estimates of some population parameter. Therefore, sampling is an important tool to be used in field work. Again, the point of sampling though, must be to answer our entomological or ecological question, not just to collect data.

The final analysis of these data, once obtained, is a huge problem area. It lends itself to treatment at a number of levels — graph plotting, "t" tests, analysis of variance, regression analysis, and other even more sophisticated techniques. These topics I will leave to those more competent than I am in statistics.

It is a consideration of the various elements which enter into effective sampling to which I will address myself — the accuracy, precision, efficiency, biological relevance, and ecological integrity

of the system. I will first define and discuss what is meant by each of these, and then I will try to illustrate how these problems can be approached with examples from research.

The Problem

At the onset I would like to emphasize that the development of an effective sampling system lies in striking a balance between these various elements. There is often no perfect solution; I would venture to say that there is never a perfect solution. The key is balance.

Taking these elements from the top we have:

(a) *Accuracy.*—Human in nature, measured by correlation between different workers or different methods of estimating the same characteristics. Error here results from fatigue, carelessness, poor instruction, confusion about borderline case decisions, etc.

(b) *Precision.*—Statistical in nature, measured by sampling error, used in determining the sample size required to estimate a mean to a certain degree of confidence.

(c) *Efficiency.*—Economic in nature, involves matching resources to statistical needs for optimal effort.

(d) *Biological relevance.*—Biological in nature. Does the sample unit selected and its attribute—the thing counted, measured, identified, pickled, or what have you—have relevance to the question asked? Are you measuring the right thing? And, if so, is its character influenced by the size or shape of the sample unit chosen?

(e) *Ecological integrity.*—Ecological and statistical in nature. Does the definition of the sampling universe coincide (overlap, if you will) with the ecological "universe"? Are you looking at all of the relevant parts of the system you are examining?

The Approach (with reference to real sampling problems).

(a) *Accuracy.*—Dissection vs. radiograph analysis. Comparison of observers. Training.*

(b) *Precision.*—Analysis of variance of brood density measure-

ments over the sampling universe.**

(c) *Efficiency.*—What size sample unit?**

(d) *Biological relevance.*—The effect of plot size on the variance: mean relationship. SAMSIM—a computer sampling simulator.

(e) *Ecological integrity.*—A critique of single parameter measurement.

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CONSIDERATIONS OF THE RELATION OF VARIOUS ERRORS TO ESTIMATES OF POPULATION CHARACTERISTICS

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Introduction

I HAVE been asked to discuss with you "the effects of sampling errors in estimating population numbers, mortality rates, etc. on the validity and/or reliability of the mathematical models developed thus far for analysis of life-table data." I must confess to some difficulty in deciding how to deal with the assignment, for it gives a lot of room in which to roam. In the end it seemed that the purposes of this workshop would be met best by attempting a simple common-sense discussion of the central, practical question: just what *is* the difference between an estimate and the true value being estimated?

This difference, called *total error,* always exists; and it is upon our knowledge of its components, their properties, and their relative sizes that we base our judgments of both the validity and the reliability of an estimate. Indeed, the whole purpose of sampling theory and methodology is to make possible the appraisal and control of total error. Despite its importance, the question of total error has been avoided or overlooked generally in the development of mathematical models of population phenomena.

Error enters estimates in many varied and often subtle ways. It is almost always the result of many factors operating simultaneously—some known, other conjectural. Total error can seldom be evaluated directly. One must usually rely on assumption, analogy, rigorous application of suitable methods, and sometimes mere guesswork in its appraisal.

To gain some insight into the problem of appraising error, we

will first identify the several kinds of error. Then, we will show how each kind can contribute to total error. And, finally, we will discuss how these contributions, in turn, are related to our judgments of the validity and reliability of estimates.

Some Fundamentals

To begin, I think it is necessary to review some of the definitions and notions that are basic to any discussion of sampling in general and of sampling errors in particular because usage tends to vary with the subject matter to which it is applied.

It must be emphasized, first of all, that any material that is to be sampled consists, at least conceptually, of a well-defined set of objects or events. The set is referred to as the *population* and the objects or events as *individuals*. The group of similar populations that contains the population of interest is called the *universe*.

In the population of interest all individuals have at least one attribute or characteristic of interest, and each individual possesses a particular *true* value of that attribute. In practice, it is convenient to speak of the set of values corresponding to the individuals in a population as *the* population.

Obviously, any set of attribute values or measurements made on a population contains information about the original population of objects or events, but that information is not very useful until it is condensed into a form that is more comprehensible than a simple list of the individual values. The device used to describe a population more succinctly is the *frequency distribution*, which is simply a tabulation of the frequency of occurrence of each value that appears in the population. Such a tabulation can be expected to contain far fewer entries than there are individuals in the population. In trivial cases it is possible to have only a single entry, but in most cases that concern us, the number of entries may be very large so that further condensation of the information is desirable or even necessary.

The most generally satisfactory method is to describe the frequency distribution in terms of its moments. The moments are

simply a series of arithmetic means of successively higher powers of the values in the population, thus

$$m_k = (1/N) \sum_{i=1}^{h} f_i \, y_i^k$$

where

m_k = the kth moment, k being the power.
N = the size of the population.
h = the number of different values (or classes) that appear in the population.
f_i = the ith frequency from the distribution.
y_i = the true value corresponding to the ith frequency.

When the frequency distribution encompasses the whole population, $h = N$ and $f_i = 1$.

The first moment, of course, is simply the well known measure of location. It fixes the position of the population (or of the distribution) within the range of values that are possible for the attribute being studied. If one is dealing with an attribute that is constant over all the individuals in the population[1], then each individual value equals the first moment which then provides a perfect description of the population with respect to the given attribute.

In contrast, if more than one value appears in a population, then the first moment is no longer a perfect description, although it still serves as a measure of location. The description can be improved by including a measure of the dispersion of the individual values, and this is provided by the second moment, which will be discussed in the next section. The first two moments usually give an adequate description of a population if its frequency distribution is reasonably symmetrical. Occasionally, the third and fourth moments will be needed to improve the description of an abnormal distribution, but higher order moments will be of use only rarely.

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[1] When all the individuals in a population have the same (constant) true value for an attribute but the value changes from one population to another, the attribute is called a *mathematical variable*. If all individuals in all populations in the universe possess the same value, the attribute is called a *mathematical constant*.

Random Variables and Random Error

Any attribute or measurement for which more than one true value can appear in the population is a *random variable,* and we have just seen that its description requires both the first moment to measure location and the second moment to measure dispersion.

The first moment of a random variable, usually called the *arithmetic mean* or simply the *mean,* also serves as a *measure of central tendency,* meaning that it is the value each individual in a population *tends* to possess. The notion here is that the mean is the value each individual *would* possess if it were not for the operation of one or more chance mechanisms in the determination of individual true values. In consequence, a true value of a random variable, Y, is conceived to have two parts: a constant part that is equal to the population mean, $\overline{Y}$; and a variable part, e, which represents the effect of chance on the value of a given individual; thus

$$Y = \overline{Y} + e$$

The population of values of the variable part, e, is the *random error.* Taking the mean of both sides of the definitional identity one gets

$$\overline{Y} = \overline{Y} + \overline{e}$$

so that $\overline{e} = 0$, which simply means that the average deviation from the population mean is zero.

As a measure of dispersion, the second moment of the random variable has the disadvantage that it depends upon the value of the first moment since it is calculated by squaring the individual values of the random variable

$$Y^2 = (\overline{Y} + e)^2 = (\overline{Y})^2 + 2\overline{Y}e + e^2$$

and then taking the mean over the population

$$\overline{Y^2} = (\overline{Y})^2 + 2\overline{Y}e + (\overline{e^2})$$

which, with $e = 0$ always, reduces to

$$\overline{Y^2} = (\overline{Y})^2 + (\overline{e^2})$$

Because the *second moment about the origin,* as it is properly called, is not comparable between similar populations with different means, it is customary to use the *second moment about the*

mean as the standard measure of dispersion; that is the average of

$$(Y - \overline{Y})^2 = e^2$$

This value, called the *population variance,* σ^2, measures the dispersion of individual values around the population mean without regard to sign. Because $\bar{e} = 0$, both the random variable and the random error have the same population variance. In fact, the random error can now be recognized as a kind of standard random variable with mean equal to zero, variance equal to the variance of the corresponding attribute, and frequency distribution equal to the frequency distribution of the attribute translated to the origin.

The concept of a random error is sometimes difficult to accept for people working to uncover casual order in living systems. Whereas the values of a random error are assumed to arise by chance, we tend to believe that the individual true values can be explained entirely by casual relations and without any recourse to random error or the laws of chance. Actually, there should be no conflict between these concepts if one keeps in mind the scope of any given problem in which the concept of random error is used. Then random error is properly regarded as that part of the individual true values *not explained within the context of the problem.*

For example, suppose the subject matter is the body size of a population of insects. The basic problem we have been discussing is the description of a population, in which case the model of an individual true value is, of course

$$Y = \overline{Y} + e_1$$

with the individual value of the random error given as

$$e_1 = Y - \overline{Y}$$

But, the problem might be to describe the relation between body size and age so that the model becomes

$$Y = \overline{Y} + a_1(A - \bar{A}) + e_2$$

so that an individual value of the random error becomes

$$\begin{aligned} e_2 &= Y - \overline{Y} - a_1(A - \bar{A}) \\ &= e_1 - a_1(A - \bar{A}) \end{aligned}$$

This may be smaller than in the previous problem. Again, the

problem might be to describe the relationship between body size and both age and nutritional level with the model

$$Y = \overline{Y} + b_1 (A - \overline{A}) + b_2 (N - \overline{N}) + e_3$$

yielding

$$\begin{aligned} e_3 &= Y - \overline{Y} - b_1 (A - \overline{A}) - b_2 (N - \overline{N}) \\ &= e_1 - b_1 (A - \overline{A}) - b_2 (N - \overline{N}) \end{aligned}$$

This may be a still smaller value for the random error. There is no theoretical limit to the smallness of the random error. If the scope of a problem were expanded indefinitely, it might be possible to decrease the size of the random error indefinitely, but one can always expect to reach a practical limit both in the scope and complexity of a problem that can be handled and in the reduction of random error long before the error is as small as is desired.

Now random error is not the only kind of error with which we must deal. On the one hand, the random error is inherent in the population; it is the variation in true value or measurement of an attribute left unexplained by the model, and we have seen that it is basic in describing the material with respect to that attribute or measurement. On the other hand, there are extraneous errors that detract from that description by distorting it in one way or another. In this category are all the errors that are inherent in the particular set of procedures by which observations are made on a population. These errors are the subject of the next section.

Extraneous Errors

There are two general types of extraneous error. One type, which we will call a *compensating error,* a, is like a random error, except that it arises from different sources and, therefore, has different interpretations. Like the random error, its first moment is zero, but its second moment is not the population variance. The second type of extraneous error we will call a *systematic error,* b, because it is always one-directional. It is, in fact, a nonzero constant, having the same value for each observation. Although we will deal with systematic error here only as an additive constant, it may also be a constant proportion of the true value of an individual. Our generalizations about systematic error will hold for either case.

Now, we can write a general model for an *observation,* Y′, on an individual in terms of its true value, Y, and its associated errors

$$\begin{aligned} Y' &= Y + a + b \\ &= \overline{Y} + e + a + b \end{aligned}$$

The mean of all observed values over the population, the *observed population mean,* is

$$Y' = \overline{Y} + \bar{e} + \bar{a} + b$$

but under these conditions $\bar{e} = \bar{a} = 0$ and only b is unknown, so

$$\overline{Y}' = \overline{Y} + b$$

As we have seen, the second moment about the mean is based on the deviations of individual values from the mean

$$Y' = \overline{Y}' = e + a$$

and the mean of these deviations squared is the *observed population variance*

$$\begin{aligned} \hat{\sigma}^2 &= (\overline{e + a})^2 \\ &= \bar{e}^2 + 2\,\overline{ea} + \bar{a}^2 \end{aligned}$$

that, under the condition that $\bar{e}^2 = \sigma^2$, becomes

$$\hat{\sigma}^2 = \sigma^2 + 2\,\overline{ea} + \bar{a}^2$$

It can now be seen how the presence of extraneous errors can detract from the description of a population. If systematic error is present, the observed population mean is distorted while the presence of compensating error distorts the observed population variance. The extraneous errors always have these specific effects, regardless of how the errors arise. In this example they could only have arisen as errors of observation or recording because no sampling is involved; but when a sample of observed values is used to estimate the true population mean and variance, the extraneous errors may consist of both these common *measurement errors* and of *sample selection errors.* It is worth noting, then, that poor observational technique has the same effect as poor sampling technique, and vice versa.

Sample-based Estimates of Population Mean and Variance

A *sample* is nothing more than a collection of observed values

taken from the population of interest. Suppose, then, that we designate each individual in the population as a possible sample of size $n = 1$. Now each individual observed value is also the mean value of one of the possible samples. If we were to arrange all the possible sample means into a frequency distribution, we would get what is called the *sampling distribution* of the population. In this special case the sampling distribution and the frequency distribution of the individual observed values are obviously the same.

It comes as no surprise, then, that the arithmetic mean of the sampling distribution is the same as the observed population mean. If each of the possible samples has an equal chance of being selected for observation this result is called the *expected value,* E, of a sample mean which may be written as

$$E\,\bar{y} = \bar{Y} + E\bar{e} + E\bar{a} + b$$

In analogy to the previous section $E\bar{e} = E\bar{a} = 0$, so that

$$E\bar{y} = \bar{Y} + b$$

Now, instead, suppose that we consider the whole population as a single sample of size $n = N$. Then, the sample variance S^2 equals the observed population variance σ^2 from the previous section and, with only one possible sample, the expected value of the sample variance must also equal the observed population variance

$$\begin{aligned} E\,\bar{s}^2 &= Ee^2 + 2E\,\bar{e}\bar{a} + E\bar{a}^2 \\ &= \sigma^2 + 2E\,\bar{e}\bar{a} + E\bar{a}^2 \end{aligned}$$

The point of these trivial exercises is to show that estimates of both the true population mean and the true population variance can be obtained from sample means and sample variances—at least in the extreme cases considered. It is not so obvious but is nevertheless true that within these limits of sample size:

1. it is always possible to obtain estimates of the true population mean and variance as well as estimates of other population parameters such as regression coefficients; and
2. the estimates are *unbiased* if, in the estimators like those modeled above, the algebraic sum of all terms that arise from extraneous errors can be shown to equal zero.

These conclusions hold—even when the possible samples have unequal probabilities of selection—provided only that:

1. every individual in the population being sampled is contained in one of the possible samples; and
2. every possible sample has a known probability of being selected for observation.

The various forms of random or *probability sampling* are the only sampling designs known to satisfy these conditions theoretically; and even they may fail to do so if not applied very rigorously, or if the estimators are not constructed to correspond properly with the structure of the samples. In general, any failure to satisfy these conditions will create additional extraneous errors of both kinds (systematic and compensating), thus increasing the hazard of bias in the estimates.

Biases in estimates of both the mean and the variance are important components of the total error with which we are concerned. The bias in the estimate of the mean, commonly known as *the bias,* B, is of particular importance as we shall see below. It measures the distance between the true population mean and the mean of the sampling distribution. Another way of viewing this bias is that estimates of the mean are unbiased if, *on the average,* the sample means equal the true population means. This is not to say, of course, that an unbiased estimate from any given sample equals the true population mean, for we know that a sample mean will deviate to a greater or lesser extent from the mean of the sampling distribution.

The second major component of total error is the average deviation of the possible sample means from the sampling distribution. It is called *sampling error,* $\sigma_{\bar{y}}$, and it is well known that the sampling error is a function (depending upon the sampling design) of the sample size and the true population variance. For example, the true (sometimes called "pure") sampling error in simple random sampling is simply

$$\sigma_{\bar{y}} = \sqrt{\sigma^2/n}$$

However, the observed sampling error, $s_{\bar{y}}$, obtained from the estimated population variance, also contains whatever bias enters that estimate by way of the procedures used:

$$s_{\bar{y}} = \sqrt{\frac{\sigma^2 + 2Eea + Ea^2}{n}}$$

The sampling error is the measure of the *precision* of the estimate of the population mean. Its important features are first, that it can be observed readily; and second, that its size can be reduced to any desired level simply by increasing sample size, or by tightening up the set of procedures used, or by both.

Accuracy refers to the magnitude of deviations of sample means from the true population mean resulting from the effects of all errors, including systematic errors. It is the total error, expressed as the square root of the *mean square error,* mse, which can be shown to equal the variance of the estimate $s_{2\bar{y}}$, plus the bias of the estimate, B.

$$\text{mse} = s^2_{\bar{y}} + B^2$$

The bias, although it ordinarily cannot be observed, is an important property of an estimate. Unlike the sampling error, its size can be reduced only by using more rigorous methods of sampling, observation, and estimation. The ratio of bias to standard deviation, B/s, is often used to judge the effects of bias.

When the ratio is less than 0.01, the bias is generally judged to be negligible, whereas a ratio higher than 0.25 is usually judged to be a serious defect.

Bias distorts not only estimates of population means but the judgments or inferences about their precision as well. For example, given a normal sampling distribution, the probability of an error greater than 1.96(s) is 0.05 without bias, but when B/s is 0.6, the probability rises to 0.09, and when B = s, the probability is 0.17—more than three times the probability without bias. Consequently, without adequate controls on the bias, statements about the precision of estimates can often be meaningless.

In summary then, we have described three significantly different types of sampling error; we have seen how bias may enter sample estimates of one or another of the population parameters; and we have seen how bias in an estimate distorts our judgments of the validity of the estimates.

The use of biased estimates in mathematical models can have

serious consequences. If the model is an equation among population parameters and theoretical coefficients, we will find that substitution of biased estimates for the parameters will result in an inequality. If the model is an equation among known parameters and unknown coefficients, we will obtain biased estimates of the coefficients. And, in either case, interpretations of the biological significance of either coefficients or variables by recourse to biased estimates of variances (and covariances) will themselves be biased because the estimates contain variation introduced in the sampling process that can completely obscure the inherent biological variation, which is assumed to be the total content of the estimate in such interpretations.

POPULATION DENSITY AND INSECT BIOLOGY: A REVIEW

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IT WAS A REMARKABLE achievement when Uvarov *(1921)*, from field observations and from examination of a large series of museum specimens, deduced that three species of morphologically and behaviorly distinct locusts, *Locusta migratoria* L., *L. danica* L., and *L. migratorioides* Reiche and Fairmaire, were actually one species, one at the subspecific level. This accomplishment was not wholly an exercise in deductive systematics, but one in applied population dynamics research as well. It is in the latter field that I will limit my remarks today.

The theory of locust phases proposed by Uvarov 46 years ago opened a whole new approach to the explanation of behavioral and biological variation among individual species that is associated with the density of their populations. He explained that the immature, but not the adult, *danica* type, indicative of low density populations, was colored differently from the *migratoria,* or high density type. Striking color differences were shown for the hoppers (immatures) as follows: " . . . it is almost impossible to find any definite type of coloration of the larvae of *danica,* which vary enormously; uniformly green forms are most common, but fawn, grey, brown, and even black ones may be met with together. Quite opposite is the case in *migratoria,* in which each larval stage exhibits quite constant colour characters. Their coloration presents a combination of black and orange-red (or yellow), the earlier stages being almost entirely black, while orange, or yellow, appears first in the third stage . . . ." In regard to adult sexual dimorphism, male *danica* were distinctly smaller than the females, which was not the case with *migratoria.* I deliberately

omit comparisons to *migratorioides,* because of its closeness to *migratoria.*

Ecologically, *danica* showed no marked habitat preference save vast waterless tracts and forests, but *migratoria* required ". . . strictly defined permanent breeding grounds." Is it possible that this statement is noteworthy in terms of endemic and outbreak populations of forest pests?

To continue: nowhere are *migratoria* eggs laid in Russia except on little, sandy, grassy islands surrounded by hundreds of square miles of dense growth of reed, *Phragmites communis* Trin. When populations attain a certain level, the hoppers form groups, group meets group to form larger groups, and their previous relatively aimless movement becomes more directional. Temperatures around 15° C. activate the hoppers. They do not move at night, but the warm rays of the morning sun make them active again and they feed. As the temperature rises the insects become still more active and they move to the ground. By so doing, they disturb other hoppers, which increases the movement of the swarm. The movement soon becomes directional, and the swarm marches. As temperatures decrease in the evening to about 15° C., the marching ceases and the hoppers climb up plants and feed, becoming comatose as the temperature drops further. This tendency of the hoppers to repeat the movements of other ones and come together has been investigated and termed "social aggregation" by Ellis *(1953).*

Mass flight of the swarm occurs when air sacs develop in the adults, and they continue to fly, maintaining their gregarious habit. They stop flying and feed when their air sacs shrink and their fat reserves are depleted. Little was known in the early days about the breeding grounds after emigration. In a footnote to his pioneer work, Uvarov *(1921)* stated a legitimate common complaint of entomologists that pests are only studied in outbreaks, and that important clues to their dynamics would come from attention during years of minimum population.

It remained for Faure *(1932)* to test Uvarov's conclusions experimentally. His noteworthy work was a result of his insight and methodology, strong financial backing, and a good supporting staff. In the end, he confidently removed the props from Uvarov's

detractors and added considerable experimental detail to the principal thesis. This is not to say that the works of Uvarov and Faure were without error, but that they made original advances in entomology with uncanny success. Now light was admitted to a room dark since at least biblical times, and between 1932 and 1939 the list of publications on this subject grew rapidly.

Within the last decade insect physiologists have carried out fruitful research on the causes of behavioral differences noted among endemic and swarming locusts. In an arena used for a behavioral study, Ellis *(1956)* showed differences in social aggregation in two species of locusts. Newly hatched desert locusts, *Schistocerca gregaria* (Forsk.), required only 1 day to attain maximum social aggregation, whereas new African migratory locusts, *Locusta migratoria migratorioides,* settled at random until they were 2 or 3 days old. With this species, maximum social aggregation required 3 or more days. Later, Ellis *(1959a)* demonstrated that, as Uvarov suggested, crowding reinforces the instinct to crowd and the important stimulus is contact—not necessarily contact with one another, but even other species of insects and moving fine wires. She concluded that social aggregation is acquired by learning because hatchlings and solitaries did not show this behavior. She also found that the offspring of crowded parents tend to be darker and march more vigorously than those from isolated parents *(Ellis 1959b)*. This is an interesting observation in the light of recent experimental work with RNA, memory, and behavior.

Delving deeper, Ellis and Carlisle *(1961)* observed that the prothoracic gland of *L. m. migratorioides* and *S. gregaria* is shaped differently and is much larger in solitary than in gregarious forms. The corpus allatum was also slightly larger among solitaries, whereas the corpus cardiacum showed no differences. They extirpated a portion of the prothoracic gland from solitaries of *S. gregaria* which resulted in similar coloration to aggregated forms. The controls underwent a blank operation and color change did not occur.

Later, Carlisle and Ellis *(1963)* injected fresh prothoracic gland extracts from the same or another species of locust into gregarious

locusts, and found that this treatment caused a significant decline in marching activity. Boiled homogenate caused the same results.

Nolte *(1964)* presented data to show that chiasma frequency was greater in newly hatched brown desert locusts, *Locustana pardalina* (Walker), from black gregarious parents than were offspring from parents in the solitary color phase. He speculated that this may be important to locusts migrating into a region quite different ecologically from the one they left.

Nolte *(1963)* postulated that a pheromone triggers color change in several species of locusts. A biochemistry student attempted to bring about the light colors of *S. gregaria* solitary hoppers by isolating them but the succeeding instars were mostly black. Poor ventilation in the laboratory during the winter was suspected as a contributing factor, and tests were designed to learn if pheromones were involved. Three species of locusts were studied, *S. gregaria, L. m. migratorioides,* and *L. pardalina.* At the conclusion of the tests, Nolte offered that the grouping of hoppers permits the accumulation of pheromone in the air around the group and that this stimulates the melanization process. He also suggested that the pheromone collects in the eggs of gregarious locusts which results in dark hatchlings, compared to light ones from solitaries. Incidentally, Faure *(1932)* imagined such a substance existed and called it "locustine."

Norris *(1964)* showed that crowding accelerates maturation in *Schistocerca* and inhibits it in *Locusta.* She also demonstrated that the presence of mature males accelerates maturation, and that groups of immature males dampen maturation. Pheromones in the mature males appear responsible for speeding up development. In *Schistocerca,* the pheromone stimulated ovarial development and readiness to copulate in the females.

Although the drama surrounding biological effects of population density opened with Uvarov's deductive conclusions, the plot thickened with some fairly recent contributions by Faure *(1943).* His were the earliest published results of studies of color changes associated with various population densities of Lepidoptera. Working with the lesser armyworm, *Laphygma exigua* (Hübner), Faure learned that when the larvae were reared in isolation they were

light in color, but when reared in groups the larvae turned dark. This discovery is similar to his findings concerning the locusts. Unlike the paurometabolous locusts, the holometabolous armyworm has no carryover of this effect. That is, hatchling locusts tend to resemble their parents in color phase, but armyworm larvae do not. Crowded armyworm larvae were more active than those reared in isolation. Faure felt that dense populations of armyworms required more time to develop, but he had no proof of this.

It wasn't until the decade of the 1950's that emphasis was directed toward the ecological implications of color variation-crowding relationships of Lepidoptera. In 1950, a brief note appeared in NATURE, telling of color variation in *Plusia gamma* L., and promising publication of much more significance later *(Williams and Long 1950)*. Subsequently, Long *(1953)* published a portion of his doctoral thesis which was concerned with the effects of population density on lepidopterous larvae. His studies emphasized color, the number of instars, pupal weight, larval and pupal developmental rates, and mortality at different densities. The principal conclusions from these studies were that larval darkening was directly related to population density, solitary larvae were somewhat heavier than those from groups, crowding increased development rate (many crowded larvae underwent fewer instars than those in isolation), and lower pupal weight and lower larval mortality were encountered in groups. The higher mortality went along with the increased number of instars among many larvae reared in isolation. The grave mistake of not keeping data separate by sex casts a shadow over the interpretation of much of the foregoing.

Utida *(1954)* found that the density of young larvae of the cowpea weevil, *Callosobruchus quadrimaculatus* (F.), has a strong influence on the physiology, morphology, and behavior of its adults. Larval density regimes resulted in the production of only parthenogenetic females which were found to have low egg deposition, flight capability, light weight, and long life. This is in contrast to a nonflying bisexual phase where the females were heavy and deposited many eggs. As a result of additional study, he concluded that the flying phase represents a field-type weevil

and the nonflying phase is adapted to storage conditions *(Utida 1956)*. I do not feel that it is important to this discussion to go further afield in the area of stored products insects, because they present special cases in their closed environments.

The crowding of certain Lepidoptera may effect changes in fecundity as indicated by oviposition plus retained eggs or simply oviposition. Unfortunately, in the literature one term is used synonymously with the other. Thus it was stated that the fecundity (oviposition) of *Plusia gamma* L. was increased by crowding, whereas it decreased in *Pieris brassicae (Zaher and Long 1959)*. It is debatable whether oviposition alone is a reliable basis for studying this relationship when dealing with reared insects. The only way of knowing this would be to collect freshly spent females in the field and determine the number of remaining eggs and oocytes. Insects may be sensitive to rearing environments and die before they have fulfilled the reproductive potential that might be attained in the field. This is true with the elm spanworm, where spent females in the field are normally almost void of eggs, but laboratory moths rarely oviposit completely—if at all in some cases.

An important discovery was that eggs from solitary rearings were significantly heavier on the average for both *P. gamma* and *P. brassicae*. In the light of work by Campbell *(1962)* and Wellington *(1965)*, the influence of egg weight on the subsequent generation should not be overlooked. These investigations also point up the need to continue studies of this nature through several generations, rather than to stop after demonstrating significant differences in egg populations.

In other work, Zaher and Moussa *(1962)* showed that females from high density larval populations of the cutworm, *Agrotis ypsilon* Rott., produced fewer eggs, and that the total duration of the larval and pupal stages was increased by rearing them in groups. Similar results were observed from what appears to be self-regulating populations of a psyllid which infests eucalyptus foliage in Australia *(Clark 1963)*. When the adults of *Cardiaspina albitextura* Taylor are crowded, they lay only one-fifth to one-third the number of eggs deposited by uncrowded females. At both high and low population densities, the mean number of eggs laid

per female on fresh foliage was twice the number oviposited on foliage previously occupied by adults of the same generation. Because high quality foliage is required by the psyllids, Clark believes that it is the limiting factor which causes violent population changes common to this insect. He concluded that high population densities of nymphs resulted in much unfavorable foliage for oviposition and the adults responded with declining egg deposition. Therefore, the loss of foliage quality dampens the psyllid population by reducing the number of oviposition sites and the amount of food available for the oncoming generation.

Coming to more familiar ground, Ghent *(1960)* showed experimentally that larval aggregations were necessary for survival of the jack pine sawfly, *Neodiprion pratti banksianae* Rohwer. Similar results have been indicated for field populations of Swaine's jack pine sawfly, *Neodiprion swainei* Middleton *(Lyons 1962)*. This is so despite heavier egg parasitism among large egg colonies than among small egg colonies *(Lyons 1962)*. Low egg populations per colony were found to have correspondingly low survival. Lyons *(1962)* suggested that low survival among eggs in small clusters might be due to an "internal factor" involving the female, and that it has nothing to do with the size of the egg clusters themselves. Quite possibly he was dealing with the maternal factors that affect progeny, as related by Wellington *(1965)*.

Later on, additional investigations were conducted to determine the elements which preclude the success of feeding by isolated sawfly larvae *(Henson 1965)*. He published the results of laboratory studies on the European pine sawfly, *Neodriprion sertifer* (Geoffroy), which indicated that isolated larvae have a low tolerance for withstanding even a slight variation from optimal conditions of food, temperature, and humidity. In the case of either group or individual rearing, brief storage of the eggs was important for eclosion and survival of early-instar larvae. Prolonged storage caused depletion of nutritional reserves.

Henson made a curious finding when he reared some isolated sawfly larvae for 4 days and then grouped them on fresh food. All these larvae died within 2 days, whereas a control reared as a group from the start survived. A test was established to learn

the population density which would have survival benefit to the sawfly, and it was learned that eight young larvae was optimum. Apparently, group feeding permits more effective feeding and allows the sawfly larvae to live, despite rearing conditions of low ambient humidities and partly desiccated food. During preliminary olfactometer studies, the presence of a feeding larva was more attractive to other larvae than whole or mashed foliage or mashed insects.

Henson concluded that in predicting population changes from generation to generation, not only would overwintering eggs have to be considered, but also the period over which they were deposited. Thus, if weather protracted the oviposition period, small scattered larval colonies with low environmental resistance might result.

The phenomenon of population density and its effects on individual or groups of Lepidoptera has received considerable attention in Japan. Hirata, at Hirosaki University, and Iwao, at Kyoto University, have conducted very interesting investigations into the mechanisms and results of variations in population density of several lepidopterous insects. Hirata's principal efforts are directed to population density studies of the cabbage armyworm, *Mamestra (Barathra) brassicae* (L.). The latest information I have shows his list of publications began with part one of a series in 1954 and ended with part eight in 1963. Naturally enough, the first paper concerned color and population density phenomena *(Hirata 1954)*. At high densities, 80 percent of the larvae became typically dark, and the remaining 20 percent kept their lighter colors. As population density increased, pupal weight decreased and the larval stage was shortened. By shortening time in the larval stage, more cabbageworms went into pupal diapause. In a later paper he reported no conspicuous effect of larval density on pupal diapause *(Hirata 1960)*. Hirata *(1963)* also observed that neither developmental velocity nor mortality was so strongly affected in crowded cultures of the cabbage armyworm as it was among solitary larvae. This is similar to the case of the armyworm, *Leucania separata* Walker, reported by Iwao *(1962)*. This noctuid had better survival on poor host material and resisted

starvation more in crowded rearings than it did in isolated rearings. Iwao *(1962)* investigated the reactions of nine species of Lepidoptera: *Parnara guttata* Bremer and Grey, a member of the family Hespelidae, and eight noctuids, *Leucania separata* Walker, *L. loreyi* Dopunchel, *L. placida* Butler, *Prodenia litura* F., *Trachea atriplicis* L., *Naranga aenescens* Moore, *Lithocodia stygia* Butler, and *Maliattha signifera* Walker. He concentrated his studies on *Leucania separata, L. loreyi,* and *Naranga aenescens* and reported on the other species in a preliminary way. All the species showed a decline of pupal weight as crowding increased. However, this was the only attribute common to all the test insects. As a result of his work, Iwao divided his insects into two categories. One, where he believed crowding lowered the metabolic activity, which increased mortality, prolonged development, and reduced fecundity. Into this class he put: *Parnara guttata, Naranga aenescens, Maliattha signifera, Leucania placida,* and possibly *L. loreyi.* The second group was categorized by increased metabolism when crowded, which accelerated development, voraciousness, and often darkened coloration. In this class were *Leucania separata, Prodenia litura,* and *Trachea atriplicis.* The first group of species live in a more solitary manner than the second group, which commonly occurs in outbreak numbers. The individual responses of the second group may give it better survival advantage under the stress of outbreak conditions. Members of the species *Leucania loreyi* and *L. placida* do not occur in outbreak, and they maintain themselves at lower population levels that do not fluctuate greatly. When crowded, they do not darken, and both larval and pupal periods are protracted.

Fecundity was affected variously with the different insect species. Significant differences were not apparent for the mean fecundity of *L. separata* or *L. loreyi* reared in isolation or in groups. Adults from isolated larval rearings of *N. aenescens* were significantly more fecund than adults from group-reared larvae. Pupal diapause also increased with population density in *N. aenescens.* In fact, under conditions that otherwise prevent diapause, this insect would diapause when reared in pairs.

Iwao *(1963)* showed that late-instar larvae of *L. separata* re-

spond to artificial stimuli in a manner related to population density. Pale larvae reared in isolation were slow to move following dropping in a test arena, whereas the dark, group-reared form moved more quickly. When the pale larvae did move they tended to go to darkened quarters. In a test in which strong wind was generated by an electric fan, the pale, individually reared larvae resisted this force, and the dark larvae fell much quicker and in greater numbers. Iwao concluded that the pale larvae are passive, station-keeping forms and the black larvae are active forms.

Although color variation had long been known among populations of elm spanworm, *Ennomos subsignarius* (Hübner), and the fall cankerworm, *Alsophila pometaria* (Harris), no immediate causative factor had been suggested for the phenomenon until recently *(Drooz 1963, 1964, 1966)*. The initial idea came about because I chanced to read the summary of Hirata's 1954 paper at the same time I noticed that some spanworm larvae I was rearing singly were light-colored, and those in pairs were brown or black. The rearings were repeated on a larger scale that same year and were augmented with other tests. Spanworm pupae, in many cases, followed the colors of their earlier larval stage. Fall cankerworm larvae were included in the study, and they too responded to population density changed by color reactions. Singly reared, the cankerworm larvae were pale green and had light-colored head capsules. Paired cankerworms had broad, black, longitudinal dorsal stripes and dark head capsules. In cases where a pair consisted of one spanworm and one cankerworm, both darkened as they would have if grouped with their own kind. The possible involvement of pheromones was ruled out in tests where air was moved from a group of spanworm larvae to single ones, food transferred from one type of rearing to another, and rearing of groups of insects in cages attached either above or below cages containing individual larvae.

With the realization that spanworm population density affected larval color, came the thought that it also might make the spanworm respond in other ways. Therefore, larval density studies were begun. Larvae were reared at three densities—1, 2, and 4 per

cage—and fed ample fresh food daily. The mean time required for completing the hatch to adult stages was significantly greater for group-reared specimens of both sexes. Male pupal weight did not vary at the densities tested, but females from isolated rearings were significantly heavier than those in groups. Among females there was a direct correlation between pupal weight and fecundity (oviposition + retained eggs), and it followed that spanworms reared singly had significantly more eggs, on the average, than group-reared spanworms. Egg production is easily studied with the spanworm because freshly emerged females contain their full complement of developed eggs, and usually only a few undeveloped eggs. Conclusions reached in the laboratory have yet to be field tested. The payoff is in the field where the vagaries of weather, biological regulators, and host reactions enter the real test arena.

Following a 7-year study of the reaction of the pine looper, *Bupalus piniarius* L., to various field densities, Klomp *(1958)* concluded that the decrease in fecundity at high population levels did not regulate the pine looper population. At least this is the result of that study in that time and place. On the other hand, Tanner *(1966)* concluded that for herbivorous insects and some vertebrates, " . . . a population's growth rate is a decreasing function of population density, and that this will result in regulation of its numbers."

I have recounted some of the research carried out on the effects of population density on insect biology. It seems to me that much of this work is contributed only in bits and pieces. Many studies lack fecundity statistics, and there is little replication or continuity. Actually, a number of generations should be used—6 to 8 perhaps, based upon the number usually involved in the expression of resistance to insecticides. In some cases, developmental statistics are not identified by sex, so it is evident that this was not taken into account. Despite the failure to answer some important questions, the results point out that with many "outbreak-type" insect species, population density should be considered as an element of a population model. The work thus far has been the concern primarily of entomologists in the field of ecology. To gain penetrating un-

derstanding of the processes of biological change due to population density, physiologists and biochemists should be engaged in this endeavor.

Field study of population density and its effect on insect biology has been lacking in all but a few important cases. Understandably, this is very difficult research to conduct under field conditions. I believe the effort should be made, however, especially after an understanding of the phenomenon has been obtained in the laboratory.

With insect species such as the elm spanworm, which I have been studying lately, the opportunity to investigate its ecology in the field might come infrequently. Therefore, it's even more important to get observations and quantitative data into print so that future investigators will be aware of them. For example, the recent elm spanworm outbreak in the Southern Appalachians eroded after 2 or 3 years in a particular locale, while it prospered on new sites. The movement of the outbreak followed prevailing winds, but most certainly local populations were not completely removed from areas where they had developed to outbreak proportions.

In our present state of affairs, we have more questions than answers. Certainly, if we hope to construct meaningful population models our research will have to be strengthened by the inclusion of other disciplines, and we should develop a carefully structured team approach. Only in this way can we gain a true understanding of the forest ecosystem, our most important renewable natural resource, and develop ecologically sound ways of controlling the destructive insects that threaten it.

Literature Cited

Campbell, I. M.
1962. Reproductive capacity in the genus choristoneura led. (lepidoptera: tortricidae). I. quantitative inheritance and genes as controllers of rates. Canad. J. Genet. Cytol. 4: 272-288.

Carlisle, D. B., and Peggy E. Ellis.
1963. Prothoracid gland and gregarious behaviour in locusts. Nature 200: 603-604.

Clark, L. R.
1963. The influence of population density on the number of eggs laid by females of cardiaspina albitextura (psyllidae). Austral. J. Zool. 11: 190-201.

Drooz, A. T.
1963. Aggregation affects color of elm spanworm larvae. U. S. Forest Serv. Res. Note SE-13, 4 pp., illus. SE. Forest Exp. Sta.

Drooz, A. T.
1964. Aggregation affects color of fall cankerworm larvae. U. S. Forest Serv. Res. Note SE-33, 2 pp., illus. SE. Forest Exp. Sta.

Drooz, A. T.
1966. Color studies of reared elm spanworm larvae and pupae. Ann. Entomol. Soc. Amer. 59: 568-573.

Ellis, Peggy E.
1953. Social aggregation and gregarious behaviour in hoppers of locusta migratoria migratorioides (R. & F.). Behaviour 5: 225-260.

Ellis, Peggy E.
1956. Differences in social aggregation in two species of locust. Nature 178: 1007.

Ellis, Peggy E.
1959a. Learning and social aggregation in locust hoppers. Anim. Behav. 7: 91-106.

Ellis, Peggy E.
1959b. Some factors influencing phase characters in the nymphs of the locust, locusta migratoria migratorioides (R. and F.). Insectes Sociaux 6: 21-39.

Ellis, Peggy E., and D. B. Carlisle.
1961. The prothoracid gland and colour change in locusts. Nature 190: 368-369.

Faure, Jacobus C.
1932. The phases of locusts in South Africa. Bull. Entomol. Res. 23: 293-427.

Faure, Jacobus C.
1943. The phases of the lesser armyworm (laphygma exigua (hubn.)). Farming in S. Africa 18: 69-78.

Ghent, A. W.
1960. A study of the group-feeding behaviour of larvae of the jack pine sawfly, neodiprion pratti banksianae roh. Behav. 16: 110-148.

Henson, W. R.
1965. Individual rearing of the larvae of neodiprion sertifer (geoffroy) (hymenoptera: diprionidae). Canad. Entomol. 97: 773-779.

Hirata, Sadao.
1954. The phase variation observed in the armyworm, barathra brassicae L. I. the relations between the rearing density, and the variation of body colour of sixth-instar larva, weight of pupa, and rate of diapause. Oyo-Dobuts. Zasshi 19: 41-46. (In Japanese, English summary only read.)

Hirata, Sadao.
1960. On the phase variation of the cabbage armyworm, barathra brassicae L. V. the effect of food plant on the density dependent variations in the larval and pupal stages. Jap. J. Appl. Entomol. and Zool. 4: 102-110. (In Japanese, English summary only read.)

Hirata, Sadao.
1963. On the phase variation of the cabbage armyworm, mamestra brassicae (L.) VIII. effect of larval crowding on the development and body colour of larvae when food is changed. Jap. J. Ecol. 13: 211-216. (In Japanese, English summary only read.)

Iwao, Syun'iti.
1962. Studies on the phase variation and related phenomena in some lepidopterous insects. Mem. Coll. Agr. Kyoto Univ. Entomol. Ser. 12, No. 84, 80 pp., illus., 3 plates.

Iwao, Syun'iti.
1963. Some behavioural changes associated with phase variation in the armyworm, Leucania separata Walker. I. Reaction of larvae to mechanical stimuli. Jap. J. Appl. Entomol. and Zool. 7: 125-131.

Klomp, H.
1958. Larval density and adult fecundity in a natural population of the pine looper. Arch. Neer. Zool. 13: 319-334.

Long, D. B.
1953. Effects of population density on larvae of Lepidoptera. Trans. Royal Entomol. Soc. 104: 541-591.

Lyons, L. A.
1962. The effect of aggregation on egg and larval survival in Neodiprion swainei midd. (Hymenoptera: Diprionidae). Canad. Entomol. 94: 49-58.

Nolte, D. J.
1963. A pheromone for melanization of locusts. Nature 200: 660-661.

Nolte, D. J.
1964. Chiasma frequency and gregarization in locusts. Nature 204: 1110-1111.

Norris, Maud J.
1964. Accelerating and inhibiting effects of crowding on sexual maturation in two species of locusts. Nature 203: 784-785.

Tanner, James T.
1966. Effects of population density on growth rates of animal populations. Ecol. 47: 733-745.

Utida, Syunro.
1954. Phase dimorphism observed in the laboratory population of the cowpea weevil, Callosobruchus quadrimaculatus. Jap. J. Appl. Zool. 18: 161-168. (In Japanese, English summary only read.)

Utida, Syunro.
1956. Differential effects of temperature, humidity and population density upon some ecological characters of the two phases. Res. Population Ecol. 3: 93-104. (In Japanese, English summary only read.)

Uvarov, B. P.
1921. A revision of the genus Locusta L (=Pachytylus Fieb.) with a new theory as to the periodicity and migrations of locusts. Bull. Entomol. Res. 12: 135-163.

Wellington, W. G.
1965. Some maternal influences on progeny quality in the western tent caterpillar. Canad. Entomol. 97: 1-14.

Williams, C. B., and D. B. Long.
1950. Phase coloration in larvae of Lepidoptera. Nature 166: 1035.

Zaher, M. A., and D. B. Long.
1959. Some effects of larval population density on the biology of Pieris brassicae L. and Plusia gamma L. Proc. Royal Entomol. Soc. (A) 34: 97-109.

Zaher, M. A., and M. A. Moussa.
1962. Effect of larval crowding on the cutworm, Agrotis ypsilon Rott. Bull. Soc. Entomol. Egypte 46: 365-372.

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Decay in the UPLAND OAK Stands of Kentucky

CLEMSON UNIVERSITY
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by Frederick H. Berry

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

Figure 1.—An even-aged stand of mature oak in Kentucky.

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ONE PROBLEM THE forester faces in managing upland oaks in Kentucky is how to estimate the amount of cull and decay in these stands. To provide this information, the Northeastern Forest Experiment Station has made a study of these oak stands, how much decay they contain, and the principal causes of the decay.

Knowing how much decay these oak stands contain is important because these stands predominate on some 11.7 million acres of the commercial forest land in Kentucky (fig. 1). All together, these upland oak stands add up to about 5 million acres of commercial forest.[1]

The upland oaks include two general forest types: the oak-hickory type and the white oak type. The major oak species that occur in these types are: scarlet oak *(Quercus coccinea* Muenchh.), chestnut oak *(Q. prinus* L.), black oak *(Q. velutina* Lam.), northern red oak *(Q. rubra* L.), and white oak *(Q. alba* L).

[1] Gansner, David A. THE TIMBER RESOURCES OF KENTUCKY. U. S. Forest Serv. Resource Bull. NE-9. 97 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa. 1968.

Field Procedures

Field work was begun in 1963 and was completed the following year. During this period 37 sample plots were established in well-stocked, undisturbed (except for fire), even-aged oak or oak-hickory stands 30 to 110 years old. Most of the plots were on the Daniel Boone National Forest.

Sample areas consisted of circular plots 1/20, 1/10, and 1/5 acre in size, superimposed on a common plot center. All living trees 3.6 inches and larger in diameter at breast height (d.b.h.) were cut on the 1/20-acre plots; trees 5.6 inches and larger were cut on the 1/10-acre plots; and trees 11.6 inches and larger were cut on the 1/5-acre plots. Data collected from trees on the 1/20- and 1/10-acre plots were weighted so that all computations were based on 1/5 acre.

General information about location, topography, aspect, age, and stand history was recorded for each plot. As trees that met specifications for the plot were tallied, they were marked with consecutively numbered tags. The diameter breast height, crown class, and tree condition were recorded; and the trees were classified as either residual (showing no external evidence of decay) or suspect (showing any significant defect). Dead trees were recorded on the tally sheet, but were not tagged or dissected.

The numbered trees were then cut at an average height of 1 foot from the ground line. The main stem and merchantable branches were marked into 4-foot lengths up to a 4-inch top diameter (inside bark). Total height was recorded. The nature, extent, and location of all surface defects were recorded. Each tree was cut into 4-foot bolts, which were examined critically for decay. Defects previously noted were examined and if decay was associated with them, this was noted on the tally sheet. Where decay appeared, its extent and dimensions were determined by splitting the bolts longitudinally.

The diameter inside bark at 16-foot intervals from stump height to a 4-inch-or-larger merchantable top was recorded. Top and bottom diameters and length of merchantable limbs were recorded. The maximum diameter of decay columns was located,

diagrammed, and recorded. Lengths of decay columns were measured in both directions from the maximum diameter and were recorded to the nearest ½ foot.

Laboratory Procedures

In the laboratory, volumes were computed in cubic feet (by Smalian's formula) from the graphic tree-measurement sheets. The gross tree volume was computed at 16-foot intervals from a 1-foot stump to a 4-inch-or-larger merchantable top diameter. No reduction in gross volume was made for trim, taper, long-butting, or breakage. Where decay was present, its volume was also computed in cubic feet and subtracted from the gross volume to give the net tree volume. We included only visible decay in our determinations of decay volume, and only the stains that were confirmed as incipient decay.

Cultures were prepared from decay samples as soon as possible to determine the fungi responsible for decay. The samples were split, and from the freshly exposed faces of the infected wood six small bits of wood were extracted with a sterilized scalpel and placed in test tubes containing 2 percent Diamalt agar. If the decay organism was not isolated on the first attempt, additional re-isolations were made from the decay samples.

Occurrence of Fungi Causing Decay

A large number of fungi can cause decay in living oaks in Kentucky. However, some species of fungi occur much more commonly than others. Although 22 species were found in association with decay in oaks, four species—*Polyporus compactus* Overh., *Stereum frustulatum* (Pers. ex Fr.) Fckl., *Poria cocos* (Schw.) Wolf, and *S. gausapatum* (Fr.) Fr. — accounted for over 50 percent of the 183 identified infections (table 1). The more commonly isolated fungi were generally well distributed among the various species of oaks.

Poria cocos, which caused a brown root and butt rot, rarely extended more than 4 feet up the trunk. *Polyporus compactus, Stereum frustulatum,* and *S. gausapatum*—all white-rot fungi—

Table 1.—*Occurrence of fungi causing decay in the upland oaks of Kentucky, by tree species*

Fungus species	Identified infections						Infections
	Scarlet oak	Black oak	White oak	Chestnut oak	Northern red oak	Total	
	No.	*No.*	*No.*	*No.*	*No.*	*No.*	*Percent*
Polyporus compactus Overh.	17	15	3	—	1	36	19.67
Stereum frustulatum (Pers. ex. Fr.) Fckl.	19	3	5	—	—	27	14.75
Poria cocos (Schw.) Wolf	2	12	1	1	—	16	8.74
Stereum gausapatum (Fr.) Fr.	9	2	—	2	1	14	7.65
Unknown H[1]	10	1	2	—	—	13	7.10
Polyporus spraguei Berk. & Curt.	9	—	—	—	—	9	4.92
Poria nigra (Berk.) Cke.	6	2	—	—	—	8	4.37
Polyporus sulphureus Bull. ex. Fr.	6	—	1	—	—	7	3.83
Poria andersonii (Ell. & Ev.) Neuman	1	2	2	—	1	6	3.28
Poria oleracea Davidson & Lombard	6	—	—	—	—	6	3.28
Steccherinum setulosum (Berk. & Curt.) Miller	—	4	2	—	—	6	3.28
Merulius tremellosus Schrad. ex. Fr.	2	3	—	—	—	5	2.73
Hericium erinaceus (Fr.) Pers.	—	—	4	—	—	4	2.19
Irpex mollis Berk. & Curt.	—	—	4	—	—	4	2.19
Polyporus dryophilus Berk.	—	—	—	4	—	4	2.19
Polyporus versicolor L. ex Fr.	—	4	—	—	—	4	2.19
Poria sp.[2]	—	4	—	—	—	4	2.19
Stereum complicatum (Fr.) Fr.	—	—	2	2	—	4	2.19
Armillaria mellea (Fr.) Quél.	2	—	—	1	—	3	1.64
Polyporus cuticularis Bull. ex. Fr.	—	—	1	—	—	1	.54
Poria inflata Overh.	—	1	—	—	—	1	.54
Stereum subpileatum Berk. & Curt.	1	—	—	—	—	1	.54
Total	90	53	27	10	3	183	100.00

[1] Misidentified as *Corticium lividum* Pers. ex Fr. in U. S. Dep. Agr. Tech. Bull. 785, FUNGI CAUSING DECAY OF LIVING OAKS IN THE EASTERN UNITED STATES AND THEIR CULTURAL IDENTIFICATION, by Ross W. Davidson, W. A. Campbell and Dorothy B. Vaughn. 1942.

[2] Possibly *Poria mutans* Pk.

Table 2.—*Fungi causing decay in the oak stands of Kentucky and their relation to the portion of the tree bole affected*

Fungus species	Identified infections			Decay volume		
	In butt[1]	In trunk	Total	In butt[1]	In trunk	Total
	No.	*No.*	*No.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*
Polyporus compactus	2	34	36	0.92	15.08	16.00
Stereum frustulatum	5	22	27	6.27	13.35	19.62
Poria cocos	16	—	16	30.41	—	30.41
Stereum gausapatum	3	11	14	2.66	16.03	18.69
Unknown H.	8	5	13	.94	4.86	5.80
Polyporus spraguei	9	—	9	13.31	—	13.31
Poria nigra	4	4	8	8.62	18.48	27.10
Polyporus sulphureus	2	5	7	1.62	7.61	9.23
Poria andersonii	2	4	6	.42	1.35	1.77
Poria oleracea	2	4	6	1.76	.64	2.40
Steccherinum setulosum	6	—	6	3.74	—	3.74
Merulius tremellosus	—	5	5	—	3.30	3.30
Hericium erinaceus	2	2	4	.80	.20	1.00
Irpex mollis	—	4	4	—	.44	.44
Polyporus dryophilus	—	4	4	—	4.28	4.28
Polyporus versicolor	—	4	4	—	1.46	1.46
Poria sp.	3	1	4	2.15	.23	2.38
Stereum complicatum	2	2	4	.34	.34	.68
Armillaria mellea	3	—	3	4.29	—	4.29
Polyporus cuticularis	1	—	1	2.98	—	2.98
Poria inflata	1	—	1	13.47	—	13.47
Stereum subpileatum	—	1	1	—	.04	.04
Total	71	112	183	94.70	87.69	182.39[2]

[1] Decay originating at stump height or below was considered as butt decay.

[2] Decay volume associated with identified infections; in addition, there were 127.82 cubic feet of decay volume in which the causal fungi were unknown.

occasionally caused a butt rot but were essentially trunk-rot fungi (table 2).

Another root- and butt-rot fungus, *Polyporus spraguei* Berk. & Curt., which caused a brown crumbly rot, was isolated from only scarlet oak *(Quercus coccinea* Muenchh.). However, this fungus has been reported from other oak species in both the red and white oak groups.[2]

Armillaria mellea (Fr.) Quél., the "honey mushroom," which also causes a root and butt rot, was isolated from three trees. Although this fungus is widespread as a saprophyte, it may also live as a parasite. It often attacks oaks and other trees already weakened by unfavorable environment, injuries, insects, or other diseases.

Some of the butt-rot fungi, such as *A. mellea* may be of more importance than shown here because badly infected trees may be subject to windthrow.

[2] INDEX OF PLANT DISEASES IN THE UNITED STATES. U. S. Dep. Agr. Handbk. 165. 531 pp. 1960.

Figure 2.—Sporophore of *Fomes everhartii* (Ell. & Gall.) von Schrenk & Spauld. on the trunk of a living scarlet oak.

Sometimes trees that suffer from butt rot show a slight swelling at the base. But this abnormality is not at all general and far from a safe criterion even when it does occur.

The majority of fungi listed in table 2 may enter either through wounds in the butt or along the trunk. However, there are some species, such as *Polyporus dryophilus* Berk., that rarely enter through butt scars but usually through wounds in the upper part of the trunk.

Most of the fungi associated with decay in oaks rarely produce sporophores or conks on living trees (fig. 2), making it often impossible to determine the causal fungus from the type of decay alone. Therefore, to identify these decay fungi, it was necessary to isolate them in pure culture and compare these unidentified isolates with sporophore isolates maintained in the culture collection at the Forest Disease Laboratory at Laurel, Maryland.

Relative Importance of Fungi Causing Decay

On the basis of cubic feet of decay, two species of *Poria* — *P. cocos* and *P. nigra (*Berk.*)* Cke. — accounted for almost one-third of the total identified decay volume (table 3). As previously mentioned, rot caused by *P. cocos* was limited to the butt log, while *P. nigra* caused both a butt rot and a trunk rot (fig. 3).

Other fungi associated with appreciable decay losses were *Stereum frustulatum, S. gausapatum, Polyporus compactus, P. spraguei,* and *Poria inflata* Overh. The first three species caused decay in both the butt and trunk, while the latter two species were entirely restricted to the butt log. Total decay volume was about equally divided between the butt rots and trunk rots.

The decay volume reported in table 3 is based on the exact dimensions of the decayed wood. Actually, the volume lost through butt and trunk rots is considerably higher in logging operations. In butt rots, for example, the total cross-section of the stem is often lost through the practice of jump-butting to the upper limit of the decay.

Table 3.—*Relative importance of fungi causing decay in the oak stands of Kentucky, by tree species*

Fungus species	Decay volume					Total identified decay volume	
	Scarlet oak	Black oak	Chestnut oak	White oak	Northern red oak		
	Cu. ft.	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Percent*
Poria cocos	12.40	4.51	11.03	2.47	—	30.41	16.67
Poria nigra	26.86	.24	—	—	—	27.10	14.86
Stereum frustulatum	6.60	6.75	—	6.27	—	19.62	10.76
Stereum gausapatum	7.31	8.20	3.15	—	0.03	18.69	10.25
Polyporus compactus	8.21	6.32	—	.98	.49	16.00	8.77
Poria inflata	—	13.47	—	—	—	13.47	7.39
Polyporus spraguei	13.31	—	—	—	—	13.31	7.30
Polyporus sulphureus	8.94	—	—	.29	—	9.23	5.06
Unknown H	5.31	.07	—	.42	—	5.80	3.18
Armillaria mellea	1.22	—	3.07	—	—	4.29	2.35
Polyporus dryophilus	—	—	4.28	—	—	4.28	2.35
Steccherinum setulosum	—	.48	—	3.26	—	3.74	2.05
Merulius tremellosus	.20	3.10	—	—	—	3.30	1.81
Polyporus cuticularis	—	—	—	2.98	—	2.98	1.63
Poria oleracea	2.40	—	—	—	—	2.40	1.32
Poria sp.	—	2.38	—	—	—	2.38	1.30
Poria andersonii	.61	.61	—	.42	.13	1.77	.97
Polyporus versicolor	—	1.46	—	—	—	1.46	.80
Hericium erinaceus	—	—	—	1.00	—	1.00	.55
Stereum complicatum	—	—	.34	.34	—	.68	.37
Irpex mollis	—	—	—	.44	—	.44	.24
Stereum subpileatum	.04	—	—	—	—	.04	.02
Total	93.41	47.59	21.87	18.87	.65	182.39[1]	100.00

[1]Decay volume associated with identified infections; in addition, there were 127.82 cubic feet of decay volume in which the causal fungi were unknown.

Figure 3.—Fire scar on scarlet oak opened to show associated decay caused by *Poria nigra*.

Entry Courts and Infection

Most decay-causing fungi are unable to penetrate the protective bark on living trees. They require a wound in the tree that penetrates to the heartwood, or dead tissue extending to the heartwood, before they can attack successfully.

Fungi that cause decay in oaks penetrate the host through numerous entry courts. The relative significance of these entry courts is summarized in table 4. Fire scars were the most important means of entry for decay fungi (fig. 4). More than one-fourth of all infections came from fire scars and almost one-third of the total decay volume was associated with fire scars. Fire scars are particularly vulnerable to decay because of the large area of exposed wood and the long period of time required for the growth of protective callus.

Table 4.—*Relationship between infection courts and incidence of infection and volume of decay*

Infection court	Infections		Volume of decay	
	No.	*Percent*	*Cu. ft.*	*Percent*
Fire scars	128	26.12	99.20	31.98
Insect wounds	78	15.92	28.00	9.03
Dead branch stubs	69	14.08	31.13	10.03
Parent stumps	41	8.37	38.21	12.32
Open branch stub scars	31	6.33	39.95	12.88
Branch bumps	31	6.33	16.33	5.26
Damaged tops	23	4.69	16.48	5.31
Roots	22	4.49	6.68	2.15
Mechanical injuries	21	4.29	11.87	3.83
Woodpecker injuries	18	3.67	5.96	1.92
Miscellaneous	13	2.65	9.79	3.16
Unknown	15	3.06	6.61	2.13
Total	490	100.00	310.21	100.00

Figure 4.—An open fire scar on black oak.

Figure 5.—Advanced decay in scarlet oak, caused by the fungus *Stereum gausapatum,* which entered through an open branch wound.

Table 5.—*The comparative effectiveness of visible defects as indicators of decay*

Defect	Frequency of occurrence			Frequency of decay
	Decay present	Decay absent	Total	
	No.	*No.*	*No.*	*Percent*
Open fire scars	30	3	33	90.91
Damaged tops	23	25	48	47.92
Closed fire scars	98	186	284	34.51
Unsound branch stubs[1]	7	37	44	15.91
Sound branch stubs[1]	11	94	105	10.48
Mechanical injuries	21	180	201	10.45
Woodpecker injuries	18	201	219	8.22
Branch bumps[1]	2	26	28	7.14
Unsound branch stubs[2]	9	121	130	6.92
Stem bulges	5	75	80	6.25
Open branch stub scars	31	938	969	3.20
Branch bumps[2]	9	366	375	2.40
Total	264	2,252	2,516	10.49

[1] 4 inches and more in diameter.
[2] 2-4 inches in diameter.

Appreciable amounts of decay were also found associated with dead branch stubs, particularly unsound stubs 4 inches in diameter and larger, parent stumps, and open branch stub scars (fig. 5). Although insect wounds were second only to fire scars as entry courts, generally relatively minor amounts of decay were associated with insect wounds. The comparative effectiveness of defects, visible on the tree surface as indicators of hidden decay, is shown in table 5. Trees frequently had more than one indicator.

Age Relationships

The gross volumes and decay volumes of sample trees were calculated by age classes to determine the relationship between tree age and decay.

Decay for all oak species averaged slightly less than 2 percent of the gross merchantable volume in cubic feet (table 6). Scarlet oak had the greatest amount of decay, followed by black oak, chestnut oak, northern red oak, and white oak, in that order. The percentage of decay ranged from 2.66 percent for scarlet oak to 0.57 percent for white oak. Even in the older age classes white oak was relatively free of rot.

It can be seen from table 6 that, generally, decay losses increased progressively with age. However, with only a few exceptions, decay was of little consequence in stands less than 90 years of age.

To bring out more clearly the relationship of decay to age, decay in trees 30 to 90 years old was compared with that in trees more than 90 years old. Decay losses averaged less than 1 percent in the former group and more than 5 percent in the latter (table 7). Apparently little decay is encountered in oak harvested before 90 years of age. And a rotation of not more than 90 years is suggested for natural stands to get the maximum volume of sound wood in the shortest time and to avoid serious losses from decay.

Diameter Relationships

When timber is sold on a tree-measurement basis, one often wants to know the probable amount of decay in trees at different

Table 6.—*Relationship between age and decay in the oak stands of Kentucky*[1]

Age class (years)	Scarlet oak		Black oak		Chestnut oak		Northern red oak		White oak		All species	
	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay
	Cu. ft.	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*
30	373.06	0.68	257.12	0.51	123.20	0.00	—	—	235.66	0.19	989.04	0.43
40	1,873.82	.39	242.46	.20	96.08	.60	—	—	667.60	.25	2,879.96	.35
50	899.04	1.27	185.17	7.13	507.94	.15	—	—	656.47	.64	2,248.62	1.32
60	554.72	4.18	768.27	.91	638.50	.22	36.62	1.80	1,001.63	.09	2,999.74	1.11
70	164.05	.98	712.53	1.30	235.75	1.41	203.88	.26	1,159.30	1.26	2,475.51	1.18
80	725.07	1.84	416.55	.31	13.18	3.34	—	—	665.22	.63	1,820.02	1.06
90	303.25	6.55	182.60	3.76	229.68	7.68	—	—	83.08	.00	798.61	5.56
100	973.15	7.58	718.15	5.90	334.30	2.68	—	—	70.28	.00	2,095.88	5.97
110	104.02	5.35	—	—	90.04	9.52	69.35	1.18	—	—	263.41	5.68
Total	5,970.18	2.66	3,482.85	2.35	2,268.67	1.84	309.85	0.65	4,539.24	0.57	16,570.79	1.87

[1] Decay indicated as percentage of gross merchantable volume.

Table 7.—*Decay in oak stands 30-90 years old and more than 90 years old*[1]

Age class (years)	Scarlet oak		Black oak		Chestnut oak		Northern red oak		White oak		All species	
	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay
	Cu. ft.	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*
30 to 90	4,589.76	1.30	2,582.10	1.26	1,614.65	0.40	240.50	0.51	4,385.88	0.59	13,412.89	0.94
90+	1,380.42	7.19	900.75	5.47	654.02	5.38	69.35	1.18	153.36	.00	3,157.90	5.84

[1] Decay indicated as percentage of gross merchantable volume.

Table 8.—*Relationship between diameter and decay in the oak stands of Kentucky*[1]

Diameter class (inches)	Scarlet oak		Black oak		Chestnut oak		Northern red oak		White oak		All species	
	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay	Gross volume	Decay
	Cu. ft.	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*	*Cu. ft.*	*Percent*
3.6- 5.5	84.04	0.24	8.80	0.55	56.48	0.07	—	—	220.80	0.74	370.12	0.64
5.6- 7.5	636.68	1.40	122.36	3.58	165.36	1.15	—	—	715.54	.48	1,639.94	1.31
7.6- 9.5	1,001.22	1.76	564.60	2.68	392.88	.66	—	—	1,211.86	.17	3,170.56	1.08
9.6-11.5	1,103.50	.30	564.88	1.60	663.26	.88	—	—	771.68	.91	3,103.32	.81
11.6-13.5	626.76	2.30	393.84	.58	407.76	1.71	—	—	792.19	.96	2,220.55	1.41
13.6-15.5	345.61	1.84	587.75	1.52	303.11	2.78	138.77	0.59	469.16	.81	1,844.40	1.54
15.6-17.5	330.29	6.61	718.07	1.88	114.52	.60	101.73	.37	358.01	.00	1,622.62	2.20
17.6-19.5	646.62	1.40	320.35	4.23	108.81	3.85	—	—	—	—	1,075.78	2.49
19.6-21.5	611.65	3.29	138.08	.66	56.49	19.53	69.35	1.18	—	—	875.57	3.75
21.6-23.5	583.81	9.75	64.12	21.29	—	—	—	—	—	—	647.93	10.89
Total	5,970.18	2.66	3,482.85	2.35	2,268.67	1.84	309.85	0.65	4,539.24	0.57	16,570.79	1.87

[1] Decay indicated as percentage of gross merchantable volume

Table 9.—*Relationship between diameter and incidence of infection in the oak stands of Kentucky*

Diameter class (inches)	Scarlet oak		Black oak		Chestnut oak		Northern red oak		White oak		All species	
	Trees	Decay	Trees	Decay	Trees	Decay	Trees	Decay	Trees	Decay	Trees	Decay
	No.	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*
3.6- 5.5	94	8.51	16	25.00	104	3.85	—	—	246	6.50	460	6.96
5.6- 7.5	116	29.31	34	23.53	50	24.00	—	—	140	14.29	340	21.76
7.6- 9.5	90	22.22	56	25.00	48	29.17	—	—	112	16.07	306	21.57
9.6-11.5	60	30.00	32	56.25	42	23.81	—	—	46	26.09	180	32.22
11.6-13.5	25	48.00	15	33.33	18	50.00	—	—	30	36.67	88	42.04
13.6-15.5	9	55.56	16	81.25	9	33.33	4	75.00	12	16.67	50	52.00
15.6-17.5	6	83.33	15	53.33	3	33.33	2	100.00	7	.00	33	48.48
17.6-19.5	9	77.78	5	60.00	2	50.00	—	—	—	—	16	68.75
19.6-21.5	7	100.00	2	100.00	1	100.00	1	100.00	—	—	11	100.00
21.6-23.5	5	100.00	1	100.00	—	—	—	—	—	—	6	100.00
Total	421	28.74	192	39.58	277	19.88	7	85.71	593	13.32	1,490	22.62

diameters. Tree diameter is, of course, a function of age. As stands increase in age, the trees increase in diameter. Hence the percentage of decay should increase with diameter as well as age.

To determine this relationship, trees in the study were divided into 2-inch diameter classes and the percentage of volume decayed was computed for each diameter class. Although for all oak species decay increased progressively with diameter, there was considerable variation within individual species (table 8). With only a few exceptions, relatively minor losses from decay were encountered in trees less than 19.6 inches d.b.h.

The relationship between incidence of infection and diameter is presented in table 9. Of the 1,490 trees in the study, 337 or 22.62 percent contained measurable amounts of decay. The percentage of all oak species with decay increased progressively with increasing diameter from less than 7 percent in the smallest diameter class to 100 percent in trees 19.6 inches in diameter and larger.

This study was part of a much broader investigation of heart rots in upland oak stands in the central hardwoods region; and eventually data from these Kentucky plots will be combined with data from plots in Ohio, Indiana, Illinois, and Missouri.

Examinations of the fungi responsible for decay in living oaks in Kentucky showed a high incidence of infection associated with four fungus species: *Polyporus compactus, Stereum frustulatum, Poria cocos,* and *S. gausapatum.* These species accounted for over 50 percent of the identified infections. In all, a total of 22 species of fungi were found associated with decay in oak. The above four fungus species, together with *Poria nigra, P. inflata,* and *Polyporus spraguei,* accounted for over 75 percent of the volume loss.

Usually some visible, external abnormality indicates defect within the tree. However, data were insufficient to determine a relationship between the type and size of visible defect indicators and the loss of cubic-foot volume. Fire scars, insect wounds, dead

branch stubs, parent stumps, and open branch stub scars were found to be important entry courts for wood-destroying organisms.

Generally, decay volume increased progressively with increasing age and diameter. With only a few exceptions decay losses in trees 30 to 90 years old and less than 19.6 inches d.b.h. were relatively minor. Therefore, a rotation of not more than 90 years is suggested for upland oak stands in Kentucky.

■

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A PHOTO GUIDE

to the patterns of

DISCOLORATION AND DECAY

in living northern hardwood trees

by Alex L. Shigo
& Edwin vH. Larson

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A PHOTO GUIDE

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HOW CAN YOU TELL?

HOW CAN YOU TELL, by looking at a living tree, what quality it has? One tree may be rotten at the core yet still may contain a large volume of high-quality wood. Another may be thoroughly sound from pith to bark yet may be so damaged by minute discolorations that it is worthless for high-quality products. How can you tell?

This guide has been prepared to help you estimate the extent and severity of discoloration and decay in northern hardwood trees. Though this certainly is not the last word on the subject, our research in this has progressed to the point where our findings, combined with the findings of others, can be put to practical use.

By dissecting living trees and studying the organisms that infect them, we now know that discoloration and decay develop in certain definite patterns. And the patterns of discoloration and decay within the tree can be predicted from external signs.

Discoloration and decay are the most serious defects of northern hardwood trees. In speaking of defect, we must distinguish between injury and damage. Injury harms the tree: damage lowers the quality of the wood. For example, a disease like vascular wilt may kill the tree but do no damage to the wood. But an insect like the cambium miner may do very little harm to the tree yet do great damage to the wood.

The unseen damage done to a tree is important in the economics of forestry. Every operation in growing a tree, harvesting it, and converting it into products costs time and money. And after all the time and money have been spent on a tree, the product made from it may prove to be not worth the effort; and the tree might have been used more profitably for some other product that does not require high-quality wood.

The increased use of veneer offers an illustration. A veneer log brings top prices. But its actual value may not become apparent till it is put on a lathe and peeled. A log that looks very good, and sound to the core, may have minute streaks of discoloration scattered all through it, so that all the veneer it produces is badly streaked with defects. On the other hand, a log that has a rotten core surrounded by clear wood may produce the highest quality of veneer.

So it is not so important how much discoloration and decay a tree has, but where these defects are in a tree. The pattern of the discoloration and decay—that's the important thing.

STUDY METHODS & MATERIALS

This guide is based primarily on the findings from a series of studies made by the senior author in northern New England. Begun in 1959, these studies are being continued in efforts to clarify further our understanding of the discoloration and decay processes.

The Species

The northern hardwoods make up one of the major forest types of northern New England. They are American beech (*Fagus grandifolia* Ehrh.), paper birch (*Betula papyrifera* Marsh.), yellow birch (*B. alleghaniensis* Britt.), sugar maple (*Acer saccharum* Marsh.), red maple (*A. rubum* L.), and white ash (*Fraxinus americana* L.).

Most of the sample trees grew in the White Mountain National Forest in New Hampshire.

The resource of northern hardwoods is plentiful today, but it contains an overabundance of poor-quality trees. Foresters repeatedly ask two questions about the northern hardwoods: What can we do to assure future crops of high-quality trees? And how can we make the most of what we have now?

The Methods

A new large-scale method of dissecting living trees was used in these studies, to get at the defects inside the tree. This might have seemed an obvious thing to try. Yet large-scale dissection had not been tried on trees—at least not in quite this way.

True, pathologists had studied decay in wood and had isolated and identified fungi. Studies had been made of the cut ends of logs. And wood defects had been studied on freshly cut boards at the sawmill. But logs taper, and many of them are not straight; and though the surfaces of lumber cut at a sawmill reveal discoloration and decay, they do not reveal the complete patterns.

The development of the gasoline-powered chain saw since World War II made possible this method of dissection. By using a portable chain saw, it was possible to go into the forest and work on living trees. One could fell a tree and cut it into bolts and disks at once and rather quickly—a tedious and discouraging job with hand saws. Moreover, it was now possible to begin at one end of a tree stem and slice it down through the middle, following the natural curve of the stem. And it was possible to cut at any spot and any angle, and to lay open any particular area of a tree for study.

After a tree had been cut open, the defects were systematically

mapped. Then, from specimens of wood taken into the laboratory, chips 1 x 0.3 cm. were cut with a gouge from clear wood, discolored wood, and decayed wood, and from the zones between —six chips in each series, at intervals up and down the tree stem. These chips were cultured on agar plates. Every organism found was recorded, and most were identified.

Scope of the Studies

During these studies more than 3,000 trees were dissected, and some 100,000 isolations were made to identify organisms. More than 10,000 photographs—both black-and-white and color —were taken to record the patterns of discoloration and decay in the freshly dissected trees. From these, 100 color photographs have been selected to illustrate this guide.

GENERAL RESULTS

As dissection of the living trees disclosed general patterns of discoloration and decay, a clear understanding about three aspects of the discoloration and decay processes emerged.

A Succession of Organisms

Decay in a tree had been thought to center about three simple events—a tree is injured: a fungus enters: decay begins. But our studies showed that a complex succession of events must take place before decay can begin. It works roughly like this—a tree is injured: the tree reacts: chemical changes take place in the wood: the wood discolors: bacteria and non-decay fungi become active: the wood discolors further: decay fungi infect: decay begins.

The process is irreversible. And it cannot be shortcut. Decay does not begin until all the other events in the succession have taken place. Decay does not begin until the wood has been discolored. And the succession may stop at any stage: the wood may become discolored but may not decay.

A Consistent Pattern

The discoloration and decay in a northern hardwood tree take a definite pattern. They form a column in the tree, related

to the location of the injury. This column can spread up and down inside the tree, but it seldom spreads outward. The diameter of the column of defect is no larger than the tree was at the time of injury. In effect, growth of the tree after the injury forms a pipe of healthy new wood, and the discoloration and decay are held within this pipe.

Discoloration not Heartwood

In some tree species, like black cherry and walnut, true heartwood forms as a result of chemical change that follows normal aging processes in the wood cells. But in northern hardwoods the darker wood is not true heartwood in this sense: it is a result of discoloration processes initiated by injury.

THE PROCESSES OF DISCOLORATION AND DECAY

The development of discoloration and decay in the wood of a living northern hardwood tree is a complex continuum of events that merge and overlap in time and place. Several columns of discoloration and decay may be present in various stages of development at the same time and place. It is difficult to say where one stage ends and another begins. But for the sake of convenience in describing the processes, we divide them into three broad stages.

Stage 1

The process begins with an injury to the tree. A branch may die or break off; insects or birds or animals may attack the tree; a fire may burn the base; or a logging machine may scrape it in passing.

Some cells are killed by the injury, and others may be injured to some degree. The injured cells are exposed to the air. At this time gases and moisture can pass out of the tree, and air and moisture can pass into the tree. These changes start chemical processes in the wood cells about the wound.

Discoloration results. It may be due to the materials formed by the chemical processes, or to the darkening of cellular material

as a result of exposure to the air. Sometimes the discoloration may be a bleaching rather than a darkening. Microorganisms are not involved.

These early discolorations do not alter the strength of the wood. And the process may stop right here. It depends on the severity of the wound and the vigor of the tree. But the discoloration may advance inward toward the pith, and around the tree.

Then in time a new growth ring forms. The first cells in this ring are different from the cells that are usually produced. They act as a barrier to the discoloration process. The discoloration seldom moves into the new cells. Instead, it moves up and down the stem within the pipe of barrier cells—but not outward into the new tissues.

The extent of discoloration depends on the vigor of the tree, the severity of the wound, and on time. Discoloration advances only as long as the wound is open. Thus the entire cylinder of wood present when the tree was wounded may not become discolored. Meanwhile the tree continues to form new growth rings that are free of discoloration.

Stage 2

Stage 2 begins when microorganisms infect. As soon as the tree is wounded, many different organisms begin to grow on the wound surface. They compete; and many do not survive. Of those that survive, only a few types are able to begin growing into the wood through the wound—only those that can thrive in the discolored wood.

These first microorganisms to invade the tree—the pioneers—are bacteria and fungi. The fungi are non-Hymenomycetes: they do not cause decay. These pioneers infect only the cells that have been altered by the chemical processes, so the new tissues formed after the injury remain free of infection.

The infected cells are further altered by the pioneer microorganisms. The discoloration may increase; the cells become more moist; pH (acidity) and mineral content of the cells rises; and certain parts of the cell walls may be eroded. The wood

affected at this stage is called wetwood, redheart, or blackheart. The process may stop at this stage.

Stage 3

Stage 3 begins when decay fungi (Hymenomycetes) become active and begin to digest the cell walls. These fungi affect only those tissues that first have been altered by chemical processes and then by the pioneer organisms. The new growth of wood that continues to form remains free of infection.

The decay process continues as long as the wound remains open. Many species of microorganisms may interact until the wood is completely decomposed. The succession of organisms does not stop when the first decay fungus enters. It stops when the tissues are completely digested.

The advancing decay column is often separated from the new white wood by a band of discolored wood. In some species the margin of this band may be bleached. The pioneer organisms remain in this band. Later, as decay continues, the decay fungi slowly digest this discolored band; and only a hard black rim then separates the by-then hollow core from the healthy white wood. This rim forms first near the wound.

To this point the process may take 40 to 50 years. Healthy white blemish-free new wood will surround the hollow core, unless other wounds have been inflicted meanwhile.

We want to emphasize this point: the processes need not go through to completion. Healing of a wound, antagonisms among organisms, unfavorable environment, and other forces may cause the processse to abate in any stage.

Importance of Time

What we have described above is a continuum of events that follows a single wound at one period in the life of the tree. But a forest tree is apt to be injured a number of times. The same processes take place each time. And the discoloration and decay processes that follow a new wound are not affected by the effects of older wounds.

THE PATTERNS OF DISCOLORATION AND DECAY

A cross-section of an ideally healthy northern hardwood tree shows a pencil-thin cylinder of pith in the center of the stem, surrounded by unblemished white wood. But what you see in most trees is a core of darker wood, of varying diameter, surrounded by white wood. The pattern of the discolored wood will depend upon what has happened to the tree: when the branches died, how fast it healed its wounds; what logging wounds it had; and how much injury was done to it by insects, fire, birds, animals, or other agents.

Central Column

The most typical pattern of discoloration is a column of discolored wood extending up and down in the center of the tree. This discolored wood is always associated with some injury to the tree, like a broken branch or stem. Where decay occurs, it occurs within this column of discoloration.

In northern hardwoods, this central column of darker wood is not true heartwood—though it is often called heartwood. It does not increase in diameter as the tree grows. The discoloration is due to changes in the wood brought about by processes that are begun by wounds or other injuries.

True heartwood does occur in some hardwood species such as black walnut, cherry, and the oaks. This darker wood is due to processes associated with normal aging of the tree. As the tree grows, the column of darker wood increases in diameter. The cylinder of true heartwood extends rather uniformly throughout the entire tree, from the base up into the branches.

Columns of discolored and decayed wood, caused by injury to the tree, can form within the column of true heartwood. These columns of discolored and decayed wood do not increase in size as the heartwood does. Of course in a tree like black walnut the difference between true heartwood and discolored wood is hard to distinguish.

The differences between true heartwood and discolored wood can be tabulated roughly this way:

Heartwood	*Discolored wood*
Process initiated by aging.	Process initiated by wounds.
Internal stimuli.	External stimuli.
Proceeds centrifugally.	Proceeds centripetally.
New tissues affected each year.	Tissues that form after wounding are seldom affected.
Oldest tissues affected first.	Youngest tissues affected first.
No hard rim at margin of white wood.	Hard rim between discolored wood and white wood.
Intermediate zone between heartwood and white wood.	No intermediate zone between discolored wood and white wood.
In ring-porous species summerwood colored mostly.	Springwood and summerwood colored.
Color mostly in cell walls.	Color in walls and cell contents.
Continuous.	In columns.
Throughout tree.	Depends on wounds.
Disrupted about wounds.	Forms first about wounds.
Stabilized.	First stage of a process that can develop further.
Mostly in ring-porous species.	In all species.
Checks radially.	Honeycomb checks, and around rings.
pH not high.	pH high in advanced stages.
Moisture not high.	Moisture high in advanced stages.
Mineral content not high.	Mineral content high in advanced stages.
Cylinders of heartwood not pointed at ends.	Column of discoloration pointed at ends.
Usually circular in cross-section.	Circular or any other configuration.
Discolors when wounded.	Does not discolor further when wounded.
No microorganisms.	Microorganisms present as the processes continue.

Multiple Columns

When a tree is injured at different times, multiple columns of discolored wood develop. The multiple columns can be seen most easily on the ends of logs, where they take on a concentric pattern or a cloud-like pattern. Very careful dissections are necessary to trace each column to its source.

If two injuries to branch stubs occur at about the same time, the two columns of defect may join to appear like one column.

But if wounds occur at different times, the processes that result in discoloration and decay begin and develop independently for each wound.

If a cylinder of discoloration is already present in the stem, a later wound does not affect it. The discoloration from the new wound forms around or beside the old column of discoloration. It may completely envelop the old column, like a pipe sliding down over a smaller pipe. Or it may develop alongside the old column in the shape of a crescent or half moon. It may be wedge-shaped in cross-section.

Major injuries to the tree—such as broken stems and branches —tend to discolor the entire core of the tree that was present at the time the injury occurred. Minor injuries such as small insect wounds may cause only localized streaks of discoloration—islands of defect within sound white wood.

Because each column of defect is separate in both time and cause, the discoloration and decay processes may be more advanced in one column than in another. Decay may form in one crescent-shaped column while other adjacent columns may be discolored but still sound. Sometimes columns of defect enclose areas of clear wood. For example, a tree may have a sound center surrounded by a ring of decayed wood.

When the wood begins to dry after the tree has been cut, checks often form between the boundaries of the defect columns. The checks often follow the growth rings—ring shake. When the defect column is a complete cylinder in cross-section, the shake may develop in a complete circle along the growth ring. Because the defect columns may be in different stages of the discoloration and decay process, the stresses that develop in drying are not uniform; so checking may occur in many different patterns.

For example, this is common in sugar maple when branch stub wounds and borer wounds occur in the same place on the stem. Honeycombing or tissue collapse may result in the moist discolored tissues. And because the beetles wound the wood in a diagonal pattern, crossing many growth rings, a jagged column of defect sometimes forms that checks in all directions when the wood dries.

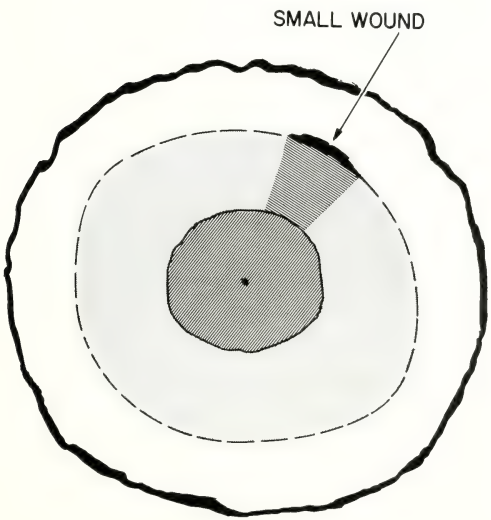
Defects under Cankers

The defects that form under cankers are somewhat different. A canker tends to produce a localized defect rather than a column of discoloration and decay.

When a canker develops about a wound, the tree usually already has a central column of discoloration and decay. The defect from a canker usually forms beneath the canker, in the wood between the central column of discoloration and the bark surface area where the canker forms. The defect from a canker usually does not spread around the entire stem: it lies immediately beneath the canker.

Mineral Streak and Stain

Wounds also begin the processes that result in the discolorations that are commonly called mineral streaks. The accumulations of salts in such discolorations may be due to the evaporation of liquids that are drawn to the exposed wound, as in a wick action. Because fungi are the agents most consistently associated with wounds does not mean that other organisms, especially bacteria, do not also alter the wood. And viruses can also cause discolorations; so they cannot be ruled out as agents inciting stain.



Even though an entire central column may not be discolored by a small wound, the whole central column may take on a slightly darker hue.

Other Patterns

The wounds caused by sapsuckers, fire, and other agents have some typical patterns, but the course of discoloration and decay follows the same patterns described above.

Sometimes, when a wound is small and not severe, the discoloration affects a small area rather than a complete new column; yet the new central column takes on a slightly darker hue —usually light pink.

EFFECTS ON DIFFERENT SPECIES

All the northern hardwood species do not react exactly the same way to injuries. Some notes about each of these species follow.

Sugar Maple

Of all the northern hardwoods, the most resistant to discoloration and decay is sugar maple. Yet many sugar maple trees are very defective. This is because some agents of injury seem to prefer sugar maple to the other species: for example, sapsuckers, cambium miners, squirrels, and—most important—the sugar maple borer. Discolorations associated with wounds of sugar maple are often called mineral streaks. Of the fungi that cause decay in sugar maple, the most important are *Fomes connatus, F. igniarius,* and *Polyporus glomeratus.*

Red Maple

In general, red maple is considered to be very susceptible to defect. Discoloration and decay advance much faster in red maple than they do in sugar maple. The central columns of discoloration are usually due to branch stubs, most of them between 4 and 10 feet up on the stem.

Sprout clumps are common in red maple, and they present some serious problems. Branch stubs on sprout stems of red maple cause more defect than the old parent stumps cause.

Many fungi cause decay in red maple, but the principal one is *Polyporus glomeratus.*

Yellow Birch

Discolorations and decays advance in this species fastest of all. Large low branch stubs—usually not well healed—are most common in yellow birch. In older trees, top breakage accounts for wide columns of discoloration. Yellow birch is one of the favorite feeding trees for sapsuckers. The most common fungi that cause decay in yellow birch are *Poria obliqua, Pholiota* species, and *Fomes igniarius. F. igniarius* var. *laevigatus* causes cankers on overmature trees.

Paper Birch

Paper birch reacts like yellow birch in most ways, except that discoloration and decay do not advance so rapidly, and large low branch stubs are not so common. Advanced decay is like that in yellow birch. The cambium miner is more common on paper birch, and so is the ambrosia beetle. Paper birch is not a favorite feeding tree for sapsuckers; but they do attack it, and heavy attacks cause black bands on the stem. The same decay fungi that attack yellow birch also attack paper birch.

Beech

The beech bark disease is the most important disease of beech. It has decimated beech in many areas.

One special feature of beech is that its base is vigorous, and wounds near the base rarely cause much damage to the roots. The notable exceptions are the defects caused by *Fomes applanatus* and *Armillaria mellea.* Because of its vigorous base, a beech tree with a defective bole may stay alive for a long time.

Ants sometimes infest wounds on beech trees, and their activities increase the defect by keeping the wound open. These insects are rarely found on other northern hardwoods.

Branches from dormant buds on the stem may cause small defects when they die.

Ash

In ash trees, most of the defect comes from the top downward. Poorly healed stubs in the crown, and broken tops, should be considered important in this species. The principal decay

fungus of ash is *Fomes fraxinophilus,* which affects the upper stem. Frost cracks are common on ash in some areas.

STUBS WITHIN THE STEM

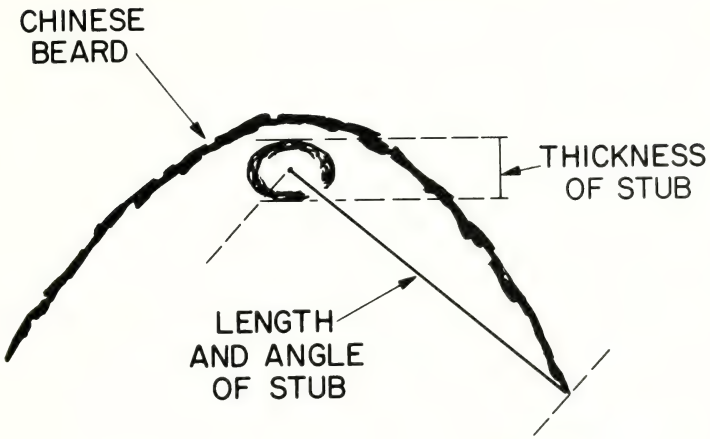
How to Estimate Size, Angle, and Depth

The size and position of a branch stub buried in the wood inside a tree can be estimated roughly from the scars on the bark. And from this in turn you can estimate the size of the defect column and the amount of clear wood outside it. Much of the information on this subject comes from research done in Europe.

Two types of bark scars provide the clues. One, called a chinese beard, is like two drooping moustaches. The other, like a mouth under the moustaches, is the more or less round scar that marks where the stub was.

The chinese beard forms this way: as a branch grows on the tree stem, a layer of thick-walled cells forms in the axil above the branch. The bark becomes roughened over this ridge of thick-walled cells. In some species, like paper birch, the bark also turns dark here.

Stub scar and chinese beard on a beech tree.



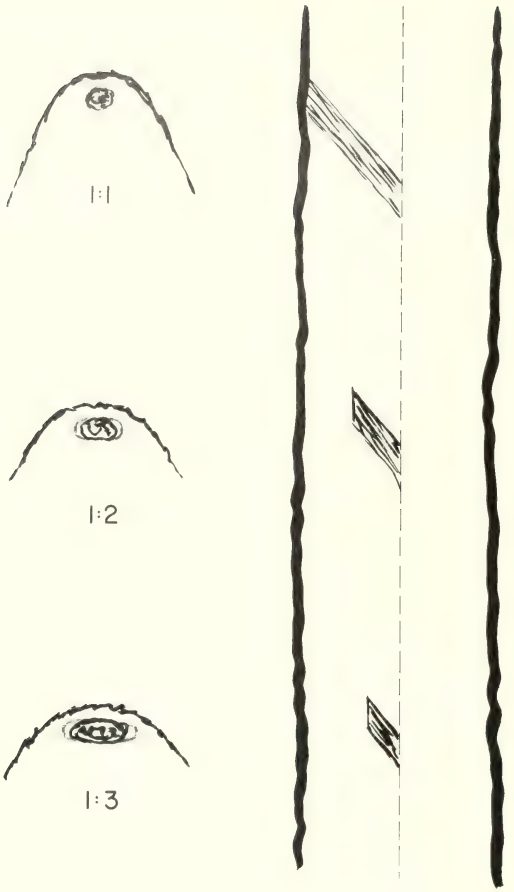
How length and angle of stub is estimated from the stub scar and chinese beard.

This scar can be used to estimate both the length of the stub inside the tree, and the angle at which the stub joins the vertical axis of the tree center. From the center of the stub scar, draw a line to the bottom end of the chinese beard. This equals the length of the stub and shows the angle at which it lies.

The thickness of the stub can be estimated directly from the stub scar. Assume that the branch that broke off to form the stub was practically round. The *height* of the stub scar shows the size. If the stub scar is about 2 inches high, the stub is about 2 inches in diameter.

How far inside the tree the stub is buried can be estimated from the *shape* of the stub scar. As a tree adds new growth rings, the growth at any one spot on the stem is outward, not upward. The height of the stub scar remains the same. But as the new growth is added, the bark is pushed outward, and the scar spreads at the sides, gradually changing in shape from a circle to an ellipse.

The scar's ratio of height to width indicates how far the stub extends from the pith center of the tree toward the bark; and this tells conversely how much new wood has formed over the stub.



Relationship of stub position to shape of stub scar.

For example, if the stub scar is round, it has a ratio of 1 : 1. This means that the end of the stub lies just at the bark surface —an unhealed stub—and no new growth covers it. If the scar is twice as wide as it is high, the ratio is 1 : 2. This means that the stub extends ½ the distance between the pith center and the bark, and that the other ½ is white wood. And if the ratio is 1 : 3, the stub extends 1/3 the distance between pith center and bark. And so on.

This rough formula can be applied to all the northern hardwood trees. As time passes, use of this formula becomes more difficult, especially on the maples.

PHOTO GUIDE

These photographs illustrate all the major defects of northern hardwoods, as we now recognize them, and the fruit bodies of the most important decay fungi.

FIGURE 1.—LOW BRANCH STUB.

This sugar maple (left) has a low stub, but the base is free of wounds. The long stub of hard wood shows that the stub has not been dead long, and that the discoloration processes have not had time to progress to an advanced stage.

Dissection (right) reveals the pattern of the discoloration. The wood at the base is clear. The column of discoloration from the large stub dwindles toward the base, but joins above with a wider column of discoloration from an older stub above, where the processes are more advanced. The wood formed after the stubs died remains free of discoloration. These discolored tissues are *not* heartwood.

FIGURE 2.—LOW BRANCH STUB, DECAYED.

This yellow birch has a low stub, and the callus ridge and advanced decay show that the stub has been dead a long time. Roughened bark at the base indicates basal wounds and root wounds typical of injury caused by logging equipment.

Dissection reveals discoloration and decay originating from both the basal wounds and the stubs above. The base is both discolored and decayed. The dark lines within the decay at the base indicate the limits of earlier columns of discoloration. The diameter of the widest column indicates the diameter of the tree when the large branch died.

FIGURE 3.—HIGH BRANCH STUB, UNHEALED.

This paper birch bolt contains a large unhealed stub from high on the tree. The decayed stub indicates advanced discoloration and some decay. The dark drooping lines of the bark scar — chinese beard — indicate the angle and length of the stub inside the stem.

The discolored wood associated with the stub is redheart — very wet and dark, and — beginning to decay. The column of defect from the stub does not enter the older central columns of defect, but extends up and down alongside them. Multiple columns of defect like this are common.

FIGURE 4.—HIGH BRANCH STUB, HEALED.

This healed stub wound on a paper birch illustrates how the position of the stub inside the tree can be estimated. The dark line of the Chinese beard shows the length and angle of the stub. The height of the stub scar tells the diameter of the stub.

Dissection shows the relationship. The length, angle, size, and depth of the stub are approximately as indicated by the external signs. Note that the stub healed before the last bit broke off, leaving a pinched-off piece; this affects the accuracy of the formula. In this bolt the discolored wood is as sound as the white wood; it is not moist (thus not redheart), and no organisms have invaded to alter the wood.

FIGURE 5.—HIGH SMALL BRANCH STUB, HEALED.

Full view of a small well-healed stub from high on a paper birch tree. The ellipse form of the stub scar (a 1 : 2 ratio) shows that the stub is buried about halfway between the tree center and the bark. Small, high, well-healed stubs like this indicate discoloration, but not decay.

Dissection reveals that the discolored wood in the stem is sound. The small stub was associated with a column of discoloration that formed after the branch died, when the tree was about 8 inches in diameter at this point. A central column of discoloration had formed earlier after branches died when the tree was about 4 inches in diameter. This is shown by the light-colored boundary streak in the discolored core. As other larger stubs died above, other columns of discoloration formed, enveloping the older and smaller columns.

FIGURE 6.—BRANCH STUBS IN SMALL STEMS.

Dissection of these small red maple stems shows that discolorations begin early in the life of the tree. At this age, poorly healed stubs give invading organisms the advantage. A young tree that tends to heal branch wounds slowly is a poor risk for a crop tree.

FIGURE 7.—*HYPOXYLON RUBIGINOSUM* ON STUB.

The red-brown patches on this large low red maple stub are fungus material that contains fruit bodies of *Hypoxylon rubiginosum,* a pioneer invader of wood. Its presence indicates that discoloration is advanced and decay is beginning. Trees that have several large low stubs like this usually have large central cores of defect. Large cracks may form under such stubs; and then the discoloration and decay processes go faster.

H. rubiginosum is one of the few non-Hymenomycetes that cause decay as well as discoloration. It is one of the most aggressive fungi in the forest. It infects both living trees and slash.

FIGURE 8.—BASAL STUB ABOVE ROOT COLLAR.

On this red maple tree a low basal stub joins the stem *above* the root collar. The color and feel of the stub indicate that discoloration and decay are associated with it. The diameter of the stub indicates the diameter of the defect column. Note also a small healed wound above the stub.

Dissection reveals the decay and discoloration in the base. The pattern illustrates the sequence of events in the discoloration and decay processes. The column of discoloration at the top is sound and dry, and no organisms are present. Below, the discoloration is darker and moist (blackheart), and contains organisms that do not cause decay. At the bottom is the dark moist core of decay, which contains decay fungi. The small island of discoloration above is due to the small wound.

FIGURE 9.—BASAL STUB BELOW ROOT COLLAR.

The large decayed stub on this yellow birch is joined to the stem *below* the root collar. This position, plus the angle of the stub, indicates that the decay does not go into the main stem.

Dissection shows that the decayed stub is separate from the main stem and does not affect it. The central column of discoloration marks the diameter of the tree when most of the branch stubs above died.

FIGURE 10.—SPINDLE-SHAPED CANKER ON STUB.

The spindle-shaped canker on this red maple formed after the branch stub was infected with *Polyporus glomeratus,* one of the principal fungi that infect red maple and sugar maple and cause cankers and decay. Sometimes a swollen area forms about the stub. The decay column usually becomes more extensive as it moves up the stem and meets other columns from higher branch stubs, then dwindles in size as it reaches the crown. The fertile stage of this fungus forms on dead and down trees, and the entire stem of a dead tree may be covered with fruit bodies in the fall.

Dissection reveals advanced discoloration and decay. Discoloration occurs first; then *P. glomeratus* infects the discolored wood. After the fungus becomes established, it kills the bark about the stub, thus forming a canker.

FIGURE 11.—SPROUT CLUMP.

A typical red maple sprout clump, formed low on the old parent stump. The parent stump decayed rapidly, so there is little connection between the old stump and the sprouts. If a sprout stem has many poorly healed branch stubs, it has little future value. But if the stubs are small, few, and well-healed, the sprouts can have good future value even if the base looks poor. The poorer sprouts can be cut without causing damage to the remaining sprouts.

Dissection shows that the base is sound, but all the stems have discoloration and decay due to branch stubs. The section at extreme left has a decayed stem stub. The next has a *Polyporous glomeratus* canker; the decay is light-colored, and the rim of the column is dark. All three sections on the right are infected with *P. glomeratus*.

FIGURE 12.—STEM STUB.

This sugar maple has a stem stub, where once the main stem broke and a branch became the new leader. Such stubs catch and hold water, and this is why they result in more damage than branch stubs of the same size and age. Sound stem stubs indicate discoloration; decayed stem stubs indicate advanced discoloration and decay. Stem stubs are usually found between 4 and 16 feet up the stem.

Dissection shows the pattern of defect from this stem stub. The wood is damaged more near the stub because this area has been affected longer. The discoloration is the diameter of the stub, and it spreads downward. The upper part of the discoloration is blackheart; the tissues are moist and infected with organisms. The lower part of the column is lighter in color, drier, and contains no organisms. The small core of defect in the new leader is due to branch stubs in the new leader.

FIGURE 13.—DECAYED STEM STUB.

The stem stub on this yellow birch decayed; and all that remains is an unhealed stub hole, indicating that the stub has been present a long time. Stem stubs like this are common on birches that have been broken by heavy loads of ice or snow. The discoloration and decay processes have had a long time to work on this tree.

Dissection shows that the older leader has completely decayed. Yet the decay fungi did not advance out into the new tissues. The columns of discoloration that formed later enveloped the old defect column.

FIGURE 14.—STEM STUB IN BEECH.

In this beech tree the original leader died at the 5-foot level. Even though the stem stub completely decayed and the tissues below were decomposed, the base of the tree contains very little defect. In beech, columns of defect narrow abruptly as they approach the base. The boundary of the discoloration column is white in beech.

Close-up of a dissected stem stub in beech. Even though the stem stub is decayed, the boundary of the decay is a hard rim, a barrier zone between the defect and the white wood.

FIGURE 15.—LOGGING WOUNDS ON SUGAR MAPLES.

These three sugar maples were wounded by logging equipment, 8 years earlier. The tree on the right is dead; it had severe root wounds. The other two have good callus growth, which indicates vigorous growth; and the well-healed stubs indicate that the wounds, though severe, did not produce extensive decay.

Dissection shows that the dead tree did not develop discoloration. In the other two trees, decay was present, but the defect ended abruptly above the wounds. The defect was wedge-shaped in cross-section. Because the trees had small, well-healed stubs, no central column of discoloration developed; and the wood was white from bark to pith.

FIGURE 16.—LOGGING WOUND ON YELLOW BIRCH.

A severe old logging wound on a yellow birch. The face of the wound is decayed, indicating decay in the tree.

The cross-section shows the effect on growth of the tree. The 2-inch central hard core of discoloration was already in the tree when it was wounded at 6 inches. The discoloration and decay due to the logging wound did not penetrate the smaller defect column. This is another example of multiple columns of defect in living trees. Just as they do not advance out into new tissues, the discoloration and decay also do not penetrate tissues affected earlier.

FIGURE 17.—LOGGING WOUND ON PAPER BIRCH.

This 100-year old paper birch has a 50-year-old wound, which extends to the base of the tree. There is a wound of similar size and age on the opposite side of the tree.

Dissection of the tree to 16 feet. The lower 8-foot section (right) has a 5-inch hollow center. Yet the decay did not go into the new wood formed after the tree was wounded. In the upper 8-foot section (left) the advance of the decay fungus can be seen as dark streaks in the wood.

FIGURE 18.—LOGGING WOUND ON BEECH.

A 100-year-old beech tree with a 50-year-old wound, which does not extend to the base of the tree. The hollow behind the wound indicates advanced decay.

Dissection shows that, although the decay is advanced, the base is free of decay. The decay column narrows abruptly above the wound. The boundary of the column is white. The decay advances farthest as a streak above the wound site.

FIGURE 19.—LOGGING WOUND ON BEECH.

This beech tree had a single wound above the base. Dissection shows that the base is clear, but discoloration and decay spread upwards. The decay fungi advanced through tissues first infected by other organisms; and decay was limited to these tissues. A white band surrounds the column of discoloration but not the decay column near the wound. The tissues in the white band contain plugged vessels.

FIGURE 20.—LOGGING WOUNDS ON RED MAPLE.

This red maple has two 8-year-old wounds, the smaller on the left facing the sun, the larger on the right mostly in the shade. The face of the small wound is white; the face of the larger wound is dark. Dark wound faces indicate more defect than light wound faces.

Dissection shows the difference on the lower 8-foot section at left. Very little defect is associated with the small white wound. But the defect caused by the larger dark wound meets the central column of discoloration from the branch stubs. In the upper sections of the tree, the larger branch stubs give rise to dark, moist discoloration and decay. Many stages of discoloration and decay processes can be present in the same stem.

FIGURE 21.—WHITE-FACED WOUND.

This white-faced wound, on a sugar maple with well-healed branch stubs, indicates very limited defect. The face of such a wound is hard, and often has tan streaks.

Cross-sections through the wound and directly above it show that the defect was limited to the wound area and did not advance above it. The discoloration did not go into the tree center. The small central defect column indicates that the tree lost most of its branches when it was about 3 inches in diameter. The white zone around the central dark columns contains wood with plugged vessels. These tissues are drier than the other tissues.

FIGURE 22.—WELL-HEALED SMALL WOUND.

This yellow birch has a well-healed wound at 5 feet. On vigorous trees shallow narrow wounds like this heal fast. Areas of smooth bark should be checked to determine whether a wound is present.

Dissection shows that hard dark tissue and wavy grain are associated with the wound. The large central defect column indicates that many branch stubs did not heal till late in the life of the tree.

FIGURE 23.—OPEN WOUND.

An open 9-year-old wound on a yellow birch with well-healed stubs. The callus and healed stubs indicate a vigorous tree.

Dissection reveals redheart associated with the wound. The infected tissues are dark red, moist, and contain decay organisms. The defect column narrows abruptly as it approaches the base of the tree. A well-healed stub is present several feet above the wound.

FIGURE 24.—ROUGH DARK WOUND.

This sugar maple has an 8-year-old wound. The callus tissue is healthy. But the face of the wound is rough, dark, and splintered; and this indicates that the defect may be serious.

Dissection shows decay typical of *Hypoxylon rubiginosum*. The dark, moist column of discoloration is wetwood or blackheart; it extends up to a branch stub at 8 feet. Note that the decay is advancing through the discolored column. In cross-section the defect area is wedge-shaped.

FIGURE 25.—*FOMES APPLANATUS* ON WOUND.

This beech tree has a large basal wound on which can be seen fruit bodies of *Fomes applanatus,* which indicates advanced decay, extending to base and roots. In beech, this is the principal fungus that infects the base. The face of the wound is dark and rough.

Dissection shows that decay extends from the base to 4 feet above the wound, where it ends abruptly. The central column of defect is very wide; this is due to the large wound and the infection of the tree base by *F. applanatus.*

FIGURE 26.—*FOMES IGNIARIUS* ON WOUND.

This beech tree had a fruit body of *Fomes igniarius* at 4 feet. Dissection reveals that decay is extensive above, where it meets defect columns from branch stubs, and narrows toward the base. The decay column is surrounded by a dark band, which is moist and contains other organisms. In the lower section is a smaller defect column that formed when the tree was young. The later defect column enveloped this small column, but *F. igniarius* did not penetrate this small column.

FIGURE 27.—*FOMES IGNIARIUS* VAR. *LAEVIGATUS.*

A 160-year-old yellow birch with a 60-year-old logging wound. The wound surface bears flat brown fruiting bodies of *Fomes igniarius* var. *laevigatus.*

Dissection shows that the decay caused by *F. igniarius* var. *laevigatus,* even after 60 years, has hardly penetrated the central column of discoloration that was formed before the wound occurred. Note that the discolored margin of the decay column is only on the wound side.

FIGURE 28.—*POLYPORUS VERSICOLOR* ON WOUND.

This yellow birch has a severe 8-year-old basal wound bearing fruit bodies of *Polyporus versicolor*. This is one of the first decay fungi to invade the dead wood on the face of a logging wound. The fruit bodies, the dark wound surface, the splintered wound face, and the poorly healed stubs indicate much defect.

Dissection to 16 feet shows the decay caused by *P. versicolor* on the lower margin of the wound, the decay caused by another fungus in the interior of the tree, and the central column of discoloration and decay associated with the branch stubs. The darker discolorations on the sections at left indicate wetwood or redheart.

FIGURE 29.—*PORIA OBLIQUA ON* OLD WOUND.

This is a sterile conk of *Poria obliqua* on an old basal wound on a paper birch. The orange-tan ooze below the conk indicates moist decay. *P. obliqua* infection causes the tree stem to swell so it resembles a bowling pin. A tree with this type of swelling can be identified at a glance as being infected with *P. obliqua.*

Dissection shows advanced decay caused by *P. obliqua.* The decay is darker and moister above the wound. This fungus can kill trees. It kills the bark slowly, and enlarges the wound. The fertile fruit body forms in the wood beneath the bark of dead standing trees. Trees infected with *P. obliqua* should be felled and left on the forest floor.

FIGURE 30.—BOWLING PIN EFFECT FROM *PORIA OBLIQUA.*

Dissection of this paper birch to 24 feet reveals the typical bowling pin swelling (butt sections, at left) caused by *Poria obliqua.* Note the range in color. The butt section at left is bright orange-tan, the middle section is tan, and the upper section (right) is light orange to pink. The discoloration and decay are most advanced at the base. The dark rims of earlier defect columns are obvious. As *P. obliqua* kills tissues about the wound, enlarging it, and as new branch stubs form, new columns form and envelop those formed earlier.

FIGURE 31.—OPEN WOUND BY SUGAR MAPLE BORER.

When injury by the sugar maple borer is severe, large open wounds result. Then the galleries made by the borers can be seen on the wound face. The sugar maple borer (*Glycobius speciosus*) has a 2-year life cycle; and in that time it normally bores in a spiral path to the center of the tree and then bores its way out again. A number of events can halt a borer; and the severity of the wound depends upon how much of its gallery the borer completes.

FIGURE 32.—SELECTIVE ATTACK BY BORER.

The sugar maple on the right was injured by the sugar maple borer at many points on the bole, but the tree on the left was not touched by them. This is common, but we do not know why. The injury done by the borer may be minor, causing no more than a small bump on the bark; or it may be a major wound, exposing the wood and the borer galleries. In an area where borer injury is common, small bumps on the bark may be signs of small aborted borer galleries. Discoloration, decay, and twisted grain are associated with these wounds.

FIGURE 33.—*FOMES CONNATUS* FRUIT BODY AND BORER WOUND.

The large fruit body on the face of the old basal wound on this sugar maple is *Fomes connatus*. It is typically white and moist, and has green moss on top. Above it is a large open wound caused by a sugar maple borer. Borer wounds can be found on all parts of the stem. These beetles apparently are attracted to the trees left after logging. We do not know whether it is the open condition of the stand or the stress after logging that favors borer infestation.

Dissection shows that the sugar maple borer attacked the tree soon after it was wounded at the base. The decay due to *F. connatus* is dark brown to black, and moist. The decay is advanced, but ends a short distance above the fruit body. Another decay fungus is advancing downward from the borer wound. The diameter of the defect column indicates the diameter of the tree when it was wounded.

FIGURE 34.—*ARMILLARIA MELLEA* INFECTING BASE OF PAPER BIRCH.

The wet orange-brown ooze at the base of this paper birch is a good indicator of *Armillaria mellea* infection. Here the bark was chipped away to show the dead area at the base of the birch and the plates of white fungus tissue. This fungus usually advances upward from the roots. Infected trees should be harvested as soon as possible.

This fungus may act either as a cambium killer, as shown here, or as a root and butt rotter, as shown in the three photographs that follow.

FIGURE 35.—COLLAR CRACK OF PAPER BIRCH.

In yellow birch and paper birch, *Armillaria mellea* infects the roots, and cracks form at the base of the trees. Once the cracks form, other decay fungi have easy access to the bases of the trees. Usually fungi that are more aggressive than *A. mellea* above the base enter at these openings. Once this occurs, the base decays fast. Such trees should be cut as soon as possible.

FIGURE 36.—HOLLOW BUTT CAUSED BY *ARMILLARIA MELLEA.*

Dissection of this beech tree shows a hollow butt (left) caused by *Armillaria mellea* advancing upward from the roots. The hollow in the upper section (right) was caused by other fungi advancing downward from branch stubs. If you see only the ends of logs, and both ends have hollow centers, you might guess that what you see is all one defect from one cause. Often this is not so. Butt decays often end abruptly in northern hardwoods.

FIGURE 37.—*ARMILLARIA MELLEA* ROOT DECAY.

The fruit body of *Armillaria mellea* at the base of this beech tree indicates root and butt decay. Fruit bodies like this can be found only in the fall. Cracks on roots and wet spots usually indicate root decay.

Dissection shows that both the butt and root are decayed. In early stages the infected wood is dark brown and very moist. Dark zone lines are common in the dark discoloration and decay. In later stages *A. mellea* decay is moist, bleached, and stringy. The fungus produces black ropy strands of mycelium that resemble shoestrings — hence the name shoestring fungus. Other organisms, especially bacteria, are associated intimately with *A. mellea*.

FIGURE 38.—NECTRIA CANKER ON PAPER BIRCH.

This target canker on a paper birch tree is caused by *Nectria galligena.* Such cankers usually begin at branch stubs. The face of the canker is hard and light in color. Very little discoloration is associated with these cankers; it may go only a few inches above and below the canker. The cankers themselves are highly decay resistant—except in trees also infected with *Poria obliqua.* Sapsuckers often tap the stem above the canker. These cankers are common on trees on poor sites, especially dry mountain tops.

FIGURE 39.—NECTRIA CANKER ON SUGAR MAPLE.

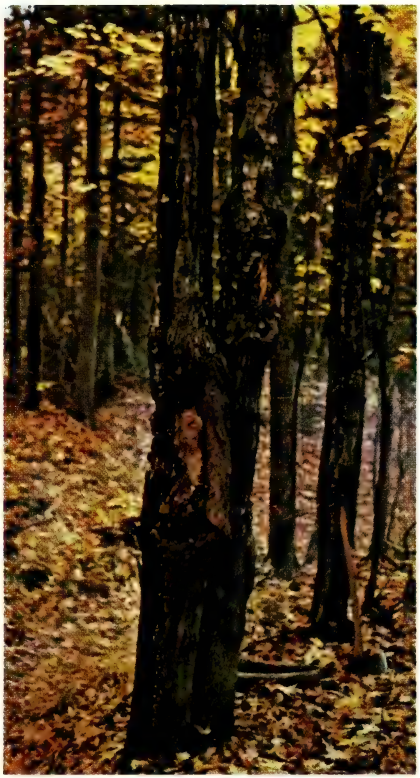
A Nectria canker on a small sugar maple. The bark is broken and the hard white surface of the wood is exposed. The minute red fruit bodies of the fungus can be found in these cankers. In some stands such cankers are common.

Dissection shows that discoloration is limited: it does not extend far above or below the canker. The wood in the canker is very dense and heavy. This canker formed below a stem stub.

FIGURE 40.—DECAY FUNGI IN CANKERS.

The canker on this sugar maple has been infected by decay fungi. Though decay fungi will infect some cankers, the advance of decay is very slow. *Fomes connatus* is one of the fungi that infect such cankers on sugar maple.

FIGURE 41.—*EUTYPELLA* CANKERS ON SUGAR MAPLE.



Eutypella parasitica caused the cankers on these two sugar maples. Decay by other fungi followed. The fruit body of *E. parasitica* is minute and black, and has a neck about 1/4 inch long.

Dissection shows that the cankers and the unhealed stubs have made these two trees worthless. However, the defect associated with the cankers alone is very slight. Stems often break at canker sites.

FIGURE 42.—OTHER CANKERS ON SUGAR MAPLE

A canker of unknown origin on a sugar maple. Such cankers are very hard. They are usually found at branch stubs. They are similar to those caused by *Polyporus glomeratus,* except that no sterile conk is present.

Dissection shows that very little defect is associated with this canker. When in doubt about a canker like this, cut it open with an ax: if you find no sterile conk, the defect will be limited to the canker area.

FIGURE 43.—STEM SWELLINGS.

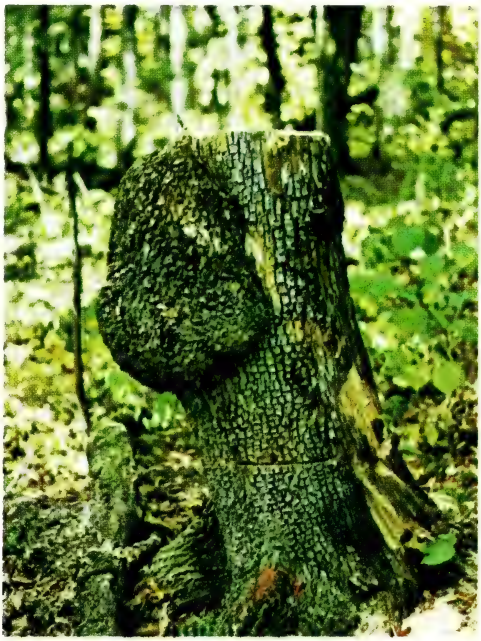
This sugar maple tree had two healed swollen areas near the base. Dissection shows very little defect. When such areas are healed tightly, very little defect is associated with them. Note that the central column of discoloration narrows abruptly toward the base. This kind of stem swelling is common in some areas.

FIGURE 44.—SUNKEN STEM CANKER.

This sunken stem canker on a paper birch is caused by *Fomes igniarius* var. *laevigatus*. These sunken cankers are most common on mature and overmature paper birch and yellow birch trees. They indicate advanced decay—especially on trees with large poorly healed stubs. The fruit body resembles a flattened fruit body of *F. igniarius*.

FIGURE 45.—STEM BURL

A stem burl on an ash tree. Burls and large swollen areas — often called tumors — can be found on all northern hardwood species. The bark is usually intact.



Dissection shows very little defect is associated with burls like this—unless the bark is broken; then decay is often present. Wavy grain is usually found a short distance above and below these abnormal growths. The cause of these burls is not known.

FIGURE 46.—FUSIFORM SWELLING.

Fusiform (spindle-shaped) swelling on the stem of a yellow birch. The bark is rough, thick, corky, and dark on these swollen areas. Swellings like this are also found on other species of northern hardwoods.

Dissection shows very little defect, except hard dark spots in the wood and some wavy grain a short distance above and below the swelling. However, if an ooze is found on the swollen area, you can expect extensive discoloration. The cause of such swelling is not known, but a disease of the outer bark after it has been wounded is suspected.

FIGURE 47.—CORKY BARK.

This sugar maple has a swollen area, with rough corky bark. The wood is not exposed as in Nectria cankers. Bark insects are common in the corky bark. Such trees are often found in clusters.

Dissection shows that only slight discoloration is associated with the swollen area under the corky bark. The wood is dense and hard, and often separations occur between some of the growth rings.

FIGURE 48.—LARGE BURLS.

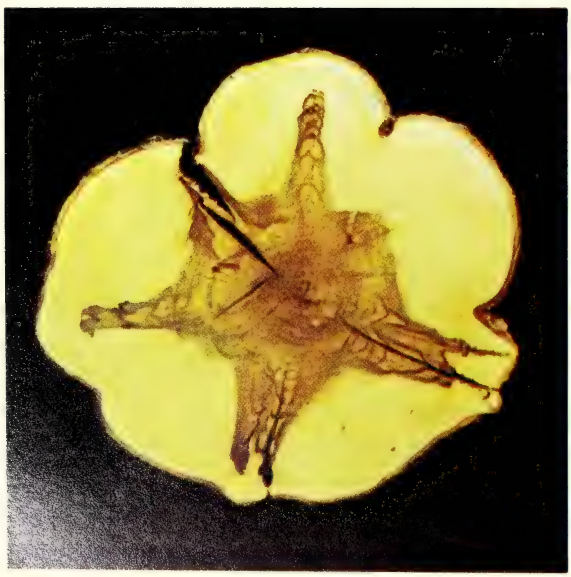
Large burls can be found on all northern hardwood species. This one is on a yellow birch. Very little defect is associated with these large burls as long as the bark is tight. Trees with burls like this are often found in clusters.

FIGURE 49.—SEAM OR FROST CRACK ON PAPER BIRCH.

The black band on this paper birch marks where cracks formed above and below a wound. The white bark usually falls away from such areas. (This should not be confused with the black bands that form after bark has been stripped off.) The cracks have lips that open in winter and close in summer. Seams or frost cracks often begin at wounds and branch stubs. Discoloration is associated with all cracks, and sometimes decay is too.

FIGURE 50.—SEAM OR FROST CRACK ON RED MAPLE.

This red maple has a large seam or frost crack, bearing a fungus fruit body. Discoloration and decay is usually associated with stem cracks like this. The open lips on this crack indicate extensive defect.



Cross-section of a red maple stem with five frost cracks shows the pattern of defect. Though the defect often is only a slight discoloration, the pattern makes it difficult to saw out a board free of discoloration.

FIGURE 51.—SAPSUCKER INJURY.

The yellow-bellied sapsucker, which drills holes in living trees, causes considerable damage in the forest.

This section of a yellow birch stem shows typical discolorations from 1-year-old sapsucker wounds. The streaks may be a few inches to more than a foot long. In cross-section they create islands of discoloration.

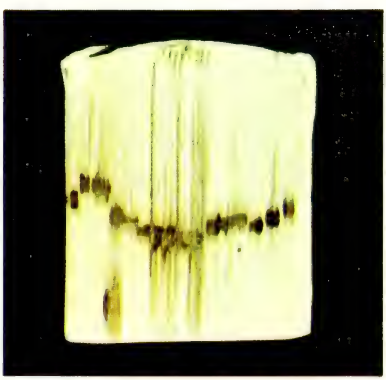
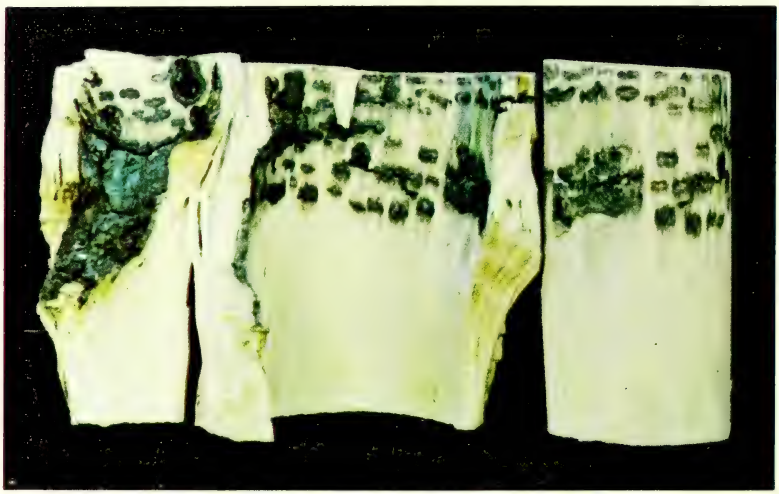


Figure 51, Continued

This shelled-out section of paper birch stem illustrates the ring shake that may form in living trees where sapsuckers have caused severe damage. Some wood shakes apart later after the boards have been sawed and dried. Drill holes made by the sapsucker can be recognized in the bark after more than 50 years.



This black band on a paper birch bolt is typical of severe injury caused by sapsuckers. Usually seen high on the tree, these bands can be found on all northern hardwood species.

FIGURE 52.—SQUIRREL INJURY.

This wound on a small sugar maple was caused by a red squirrel. Red squirrels bite young trees in the spring to start sap flows, which they drink. The teeth marks can still be seen on the wound surface.

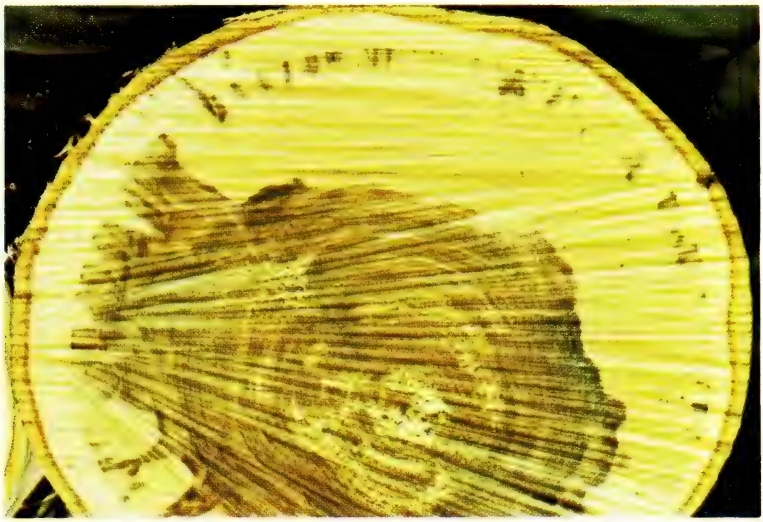
Dissection of a small red maple shows the discoloration caused by injuries inflicted by a red squirrel.

FIGURE 53.—AMBROSIA BEETLES.

The bleeding from this paper birch is from holes made in the bark lenticels by ambrosia beetles. Small bleeding spots like these can be found on all northern hardwood species; and dead spots in the bark are usually associated with them. Bleeding spots may indicate early canker formation.

A hole made in a paper birch by an ambrosia beetle. The discoloration extends several inches above and below the hole. Small holes in bark lenticels signal this kind of defect. Such trees should not be used for veneer.

This cross-section of a paper birch bolt shows the islands of discoloration due to holes made by ambrosia beetles. The islands in some areas merge with the central column of discoloration.



These bolt ends show effects of a light infestation by ambrosia beetles.

FIGURE 54.—CAMBIUM MINER (PHYTOBIA SP.).

This piece of paper birch veneer shows damage due to the cambium miner. Defects like these are sometimes called worm tracks. The injury to the tree is slight, but the damage to the wood is great. The injury can be seen as soon as the tree is cut. In cross-section the insect galleries appear as brown to orange-brown pencil marks about 1/16 to 1/8 inch long within the growth rings. If the marks are concentrated in the center of the tree, little damage is done. But if they are scattered throughout the stem, it is ruined for veneer. Cambium miner marks occur in all the northern hardwood species. In the maples they are brown.

FIGURE 55.—PORCUPINE INJURY.

The wound at the base of this beech tree was caused by porcupines. They attack all the northern hardwood species. The teeth marks can be seen even after the wounds are very old. These wounds should be regarded like any other kind of mechanical wounds. Discoloration is commonly associated with them; and decay is associated with old wounds that have dark splintery surfaces. Beavers cause similar injury.

FIGURE 56.—*FOMES CONNATUS.*

The fruit bodies of *Fomes connatus* on this beech tree indicate decay. This fungus causes advanced decay in maples and beech. The decay is dark, wet, and spongy. The decay column ends abruptly a few inches to a few feet above the wound.

FIGURE 57.—*FOMES FOMENTARIUS.*

Fomes fomentarius is common on beech trees injured by the beech bark disease. This fungus usually infects recently killed tissues. Decay is usually limited to the area killed by other agents.

FIGURE 58.—*FOMES IGNIARIUS.*

Seen here on beech, *Fomes igniarius* fruit bodies are common on all northern hardwood species. The fruit body has white flecks inside; these can be seen easily by splitting the fruit body open. Decay caused by this fungus narrows abruptly near the base. How far it extends above the infection depends on other wounds in the tree.

FIGURE 59.—*PHOLIOTA* SP.

Pholiota sp. is a major decay fungus that often goes unnoticed. It is common on the birches, but can be found also on other species. The decay this fungus causes is usually extensive, especially in trees with poorly healed stubs.

Here are the things to look for in estimating the type and extent of discoloration and decay in living northern hardwood trees. Please bear in mind that this is the best information we have now. Research is being continued; and as new knowledge about discoloration and decay is acquired, we hope to be able to refine and modify this guide.

This list of external signs to consider is ranked from the most important to the least.

Branch Stubs

First consider branch stubs—the stubs left where branches have broken and died. In general, large branch stubs 4 to 16 feet up the stem on trees nearing maturity cause the most defect. Stubs in the crown have little effect on the central column of discoloration. Here are the main signs:

- Small branch scars, all well healed: a tree of high vigor, with a small central column of discoloration.
- Many branch scars 4 to 16 feet up the stem, not all well healed: a tree of medium vigor, with a medium-size central column of discoloration. The column tapers toward the base and toward the crown.
- Most stubs well healed, except a few large open stubs at 4 to 16 feet: the discoloration column will be irregular in form.
- Many poorly healed branch stubs: a large central column of discoloration, moist wood, and probably decay.
- Stubs that join the stem below the root collar usually do not affect the main stem. Stubs that join above the root collar cause the most defect. And the farther up into the crown, the less the damage.

Stem Stubs

A stem stub marks where at some time the main stem of the tree has broken, and a secondary stem or branch has taken over dominance to develop into a new main stem. Stem stubs can oc-

cur at any point on the stem, from base to crown; but they are most common between 4 and 16 feet up the stem.

If the remains of the stub can be seen, the size of the defect can be estimated easily: the defect column is the diameter of the stub; and it goes toward the base, narrowing as it nears the base.

Sprout Clumps and Branch Stubs

For sprout clumps, consider first the branch stubs, then the condition of the clump base. A sprout with well-healed branch stubs and a doubtful base is a better risk than a sprout with poorly healed branch stubs and a sound base. A stub with a swollen knot or a spindle-shaped canker *(Polyporous glomeratus)* signals a serious defect. Sprouts with well-healed branch stubs can be cut out of a clump without causing serious damage to the other sprouts of the clump.

Decay-Causing Fungi

Branch stubs are the main entry point for decay-causing fungi. Other types of wounds come second. Branch stubs give entry to the deep interior of the tree; mechanical wounds expose only the exterior layers of wood. Different decay-causing fungi enter these different types of wounds. The principal decay-causing fungi found in an undisturbed area will be different from those found in a logged area where there are many mechanical wounds.

An ooze flowing from an open stub or wound indicates wet-wood or decay, or both. The ooze kills algae growing on the bark, and a bleached area becomes evident. Many fungi produce fruit bodies or sterile masses of fungus tissue on branch stubs or other wounds. Some of the more important fungi to look for are:

Poria obliqua.—The black sterile conk, common on birches, indicates advanced decay. The amount of decay can be judged by the number of poorly healed stubs and other wounds. It may range from 2 to 4 feet above and below the sterile conk, on trees with well-healed stubs, to the entire stem of trees with poorly healed stubs.

On trees with advanced decay, the fungus causes swelling about the entry point. This is easy to see, because the swollen part takes the shape of a bowling pin.

This fungus kills the cambium, and a canker forms. An ooze below the canker indicates a very moist column of decay. The conk also forms on other types of wounds. In advanced stages, the sterile black conks begin to break out at other places on the bark. At this stage the tree is a total loss. Because the fertile stage of the fungus forms beneath the bark of standing trees, infected trees should be felled rather than girdled.

Polyporus glomeratus.—Small masses of sterile black fungus tissue—in swollen knots and spindle-shaped cankers on maple and beech trees—indicate advanced decay. As with *Poria obliqua,* the extent of decay can be judged from the condition of other entry courts: from a few feet to the entire stem.

To determine whether this fungus is present, cut into the swollen knot or spindle-shaped canker: a black cinder-like material flecked with dark brown areas indicates *P. glomeratus.* Also, the decayed wood has a strong medicinal odor.

The length of the spindle-shaped canker equals the length of the defect in the outer portion of the tree. The total defect extends from the central column to the bark, directly below the canker.

Because *P. glomeratus* seldom infects wounds other than branch stubs, the infection points are usually at least 6 feet high on the stem. The bases of infected trees are seldom decayed by *P. glomeratus.* Because the fungus infects stubs, and stubs form up on the bole as branches die, the decay is usually more severe above the lowest point of infection.

It is because of this fungus that branch stubs are more important than parent stumps as infection centers for decay in sprout clumps of red maple.

Fomes igniarius.—This fungus forms a black fruit body on all northern hardwood species. Split it with an ax; and you will see white flecks inside. The fruit body is found on both branch stubs and other wounds. A light-colored dry rot, usually with dark zone lines, is caused by this fungus.

A variety of this fungus, *F. igniarius* var. *laevigatus,* is common on birches. It has a flattened surface; and it is associated with sunken cankers, usually on overmature trees. These fruit

bodies indicate advanced decay, from a few feet to the entire stem, depending on the presence of other infection courts. The decay column usually narrows near the base. This is one of the most common fruit bodies on northern hardwoods.

Fomes applanatus.—The light-colored shelf-like fruit body of this fungus (often called "the artist's conk" because it has a smooth white undersurface that people have found they can draw on) occurs on all northern hardwood species, usually on wounds and stubs low on the stem. This fungus rots the roots and base of a tree, and causes a wide column of discoloration. The decay caused by *F. applanatus* narrows abuptly as it advances above the wound, unless the tree has other wounds and poorly healed branch stubs on the lower 16-foot section of stem. This fungus continues to grow and produce spores for many years on dead and down logs.

Fomes connatus.—The spongy white fruit body, often covered on top with green moss, is found commonly on maple and beech trees. The presence of the fruit body indicates advanced decay, but the decay ends abruptly above and below the wound unless other wounds are present. This fungus usually infects low wounds; it is most common below 8 feet on the stem. It infects the base of the tree but seldom causes much decay, even when large fruit bodies are present. Decay generally is limited to the lower part of the stem.

Fomes fomentarius.—The fruit body is light gray, and the bottom surface is light in color. It is found on all northern hardwood species. This fungus usually infects dead wood. For example, it is common on beech trees injured by the beech bark disease. Where you find *F. fomentarius,* look for other injuries. The decay is limited to the outer layers of wood under the bark. This fungus seldom infects discolored wood.

Fomes fraxinophilus.—The light gray fruit body usually occurs high on the stems of white ash trees; so it is hard to see when the tree is in leaf. It indicates advanced top decay. On trees with many open branch stubs, the decay may spread down to the 16-foot level.

Armillaria mellea.—This is the honey mushroom, also known as the shoestring mushroom; and it is common in clumps at the

base of northern hardwood species. The cap is light honey-brown, and there is a ring on the upper stem. The fruit body is found in September and late fall. This fungus rots roots, and causes cracks to form at the base of some trees. In birches the condition is called collar crack.

In some areas this fungus builds up heavily, especially where soils are thin and cutting has been heavy over many years, leaving an abundance of root wood in the soil as a food base. Such areas are common where balsam fir is cut; and basal cracks on balsam fir trees are good clues to root-rot areas. Birch trees growing in such areas often have root decay. Many trees with upturned knobby roots are good evidence of this.

Birches with collar crack should be cut as soon as possible. Once the cracks form, other decay fungi get in and begin to rot the stem. This root-rot fungus causes more damage to forest trees than is commonly realized.

***Pholiota* species.**—Although one of the major species has been identified as *Pholiota squarrosa-adiposa,* other species may be involved, so for this we use the general term *Pholiota* species. These fungi produce yellow to light tan fruit bodies, with scales on their caps, on all species of northern hardwoods—but most commonly on the birches. The fruit bodies can be seen only in the fall. These are among the principal decay fungi, but they often go unnoticed because the fruit body is not perennial.

Pholiota species are associated with advanced decay. They are most common on branch stubs on the lower stem. The firm light-colored to yellow decay narrows above the wound unless there are other branch stubs above; and when the stubs above are well healed, the decay ends within 3 or 4 feet. The decay narrows toward the base of the tree, and the base itself is usually sound.

Stereum murraii.—This fungus causes a canker and white rot of maples and birches, especially red maple and yellow birch. The cankers are common about branch stubs. The cankered part of the stem is flattened, and dull white crust-like patches of the fruit body form on the face of the canker. Decay is limited to about a foot above and below the canker on pole-size trees. On

overmature trees the decay is extensive, especially on yellow birch. The fungus fruits abundantly on dead and down trees. The infected wood has a distinctive odor.

Stereum complicatum.—This is one of the first decay fungi to infect the dead faces of logging wounds. A white decay results. The fruit bodies of *Stereum* species are thin, tough, and have a very smooth light undersurface.

Polyporus versicolor.—Like *Stereum complicatum, Polyporus versicolor* also is found on the dead faces of logging wounds. The fruit body is thin and varies in color; the undersurface is white with many small pores.

Hericium species.—These include the coral fungi and the bear's head fungi. They cause a moist dark decay. The fruit bodies are found in the fall.

Hypoxylon species.—The major species that infect northern hardwoods are *H. rubiginosum, H. cohaerens,* and *H. coccineum.* Their presence indicates early decay. They produce brown to brick-red patches 1 to 12 inches long, or circular mounds 1/4 to 1/2 inch in diameter, on wound faces or branch stubs.

Daldinia concentrica.—This fungus also produces brown to brick-red circular mounds, 1/2 to 3 inches in diameter, on wound faces and branch stubs. It indicates early decay. Species of *Hypoxylon* and *Daldinia* are not closely related to the common decay fungi, yet they do cause decay.

Logging Wounds

Logging causes many wounds of northern hardwood trees. Tractors and skidding machines scrape against trees and injure the base and roots; trees along skid trails are skinned by logs being skidded past; and falling trees fall against standing trees and scrape them. Though some breaking of branches may be due to logging, we consider logging injury mainly as wounds near the base of the tree. Here are some of the features of logging wounds to look for:

- A dark surface on a wound indicates more defect than a hard white surface. A rough surface indicates more defect than a smooth surface.

- Wounds below the root collar injure the base of the tree; wounds above the root collar seldom injure the base.
- Root wounds, which may be hidden by leaves and litter, may result in basal decay.
- Defects are limited to the wood present when the tree was wounded. How far the defect extends into the tree depends on the severity of the wound.
- Multiple wounds on the same tree result in severe defect.
- Logging wounds on trees with well-healed stubs indicate less defect than similar wounds on trees with many open stubs.
- Fruit bodies of fungi indicate decay.
- Vigorous callus indicates limited decay.
- Healed wounds indicate limited defect; but some wavy grain can be expected around healed wounds.
- Where insects bore into the tree through logging wounds, considerably more defect can be expected.
- The fungus fruit bodies common on logging wounds—and that can be seen easily—are, in order of appearance: *Hypoxylon* species, *Stereum complicatum, Daldinia concentrica, Polyporus versicolor, Polyporus* species, *Pholiota* species, *Fomes applanatus, Fomes igniarius,* and *Poria obliqua.*

Sugar Maple Borer

The sugar maple borer *(Glycobius speciosus)* bores through the bark into the wood of sugar maple trees. This beetle has a 2-year life cycle: 2 years from the time it enters the tree till it emerges. During this time any number of events may occur to kill the beetle; so the wound and the defect may vary from minor to severe, depending on how long the beetle is in the tree. In high winds, trees often break at the site of borer wounds.

In the beginning the gallery the beetle makes is small. Minor wounds heal, leaving small raised areas on the stem. Small galleries can be found by cutting into the small closed wounds. As the wounds become more severe, the bark falls away, and the

gallery of the beetle is exposed. Some of the borer holes may be ½ inch in diameter and several feet long. The beetle spirals around and into the stem.

Discoloration is common both above and below the wounds; and decay may be associated with big old wounds. *Fomes connatus* may infect these wounds. The defect is continuous near the wound; but as the discoloration spreads, it forms streaks of discoloration. The pattern is like a hand with outstretched fingers. A cross-section of the stem at the palm of the defect reveals a solid continuous defect; but a cross-section through the fingers shows island of defect. These are often called mineral streaks.

Sapsucker Wounds

The yellow-bellied sapsucker *(Sphyrapicus varius),* a species of woodpecker, feeds on all northern hardwood species, drilling into the tree to drink the sap. Sapsucker feeding trees are often found near the margins of areas recently logged, or near roadsides in full sunlight. There is some indication that sapsuckers prefer trees already weakened. The wounds they make have three patterns:

1. Rows of wounds scattered over the stem. These wounds cause streaks of discoloration, some extending a foot or more above and below the wound—especially in yellow birch. In cross-section of the wood, the discoloration looks like small islands. On sugar maple, the sap that flows from such wounds is often covered by black fungi; so black bark on sugar maple is a good sign of sapsucker injury.

2. Wounds concentrated in one spot, in one season. This kind of wound often causes a dark band on the tree. Discolored streaks form above and below such wounds. Also, ring shake is associated with such wounds; the extent of the shake depends upon the severity of the wounds and the time since wounding.

3. Wounds concentrated in one spot, over several seasons. These are found on feeding trees that the sapsuckers revisit year after year. The sapsuckers drill all around the top of the tree. Decay often forms behind the large open wounds. Squirrels and other small animals enlarge the wounds and aggravate the injury. These wounds can kill the section of stem attacked and the

branches above. When the wounds encircle the stem below the crown, the entire tree may die.

Cambium Miner

The cambium miner *(Phytobia* species: more than one species may be involved) attacks all species of northern hardwoods. This fly lays eggs on the upper branches of the tree. The young larvae mine down the stem through the cambium and often into the adjacent wood. The minute wounds they make in the wood cause small discolorations called pith flecks.

These marks can easily be seen on the freshly cut stump or log end, like pencil marks 1/16 to ⅛ inch long along the growth rings. In birches the flecks are red-brown, in maples dark brown.

The amount of this defect that can be accepted depends on the product. For example, if the marks are many, and in the outer layers of wood, the stem usually cannot be used for veneer, for the flecks will appear on the veneer as long streaks. If the marks are confined to the central core, the stem can be used for veneer. As the logs age, the marks become harder to detect.

Squirrel Wounds

Early in the spring red squirrels *(Tamiasciurus hudsonicus)* inflict feeding wounds on smooth-barked young sugar maples and red maples. The squirrels bite the trees, usually on the south side, to start the sap flowing; then they drink the sap after it has begun to evaporate. Black-green streaks of discoloration form above and below the wounds; and various organisms infect some wounds and cause cankers. The tooth marks of the squirrels persist for at least 10 years on the wound faces.

Ambrosia Beetles

The ambrosia beetle *(Xyloterinus politus)* attacks birch trees that have already been wounded and weakened by other agents. The adult beetles bore into the tree at the lenticels to lay their eggs; and the young develop in the tree, which may continue to lose vigor and finally may die.

When a tree recovers, the beetles leave; but their small galleries in the wood remain. Discolorations form above and below the wounds. The number of holes in the lenticels indicates the

number of discoloration streaks. As the tree grows older, the bark thickens about the holes, and nodular mounds form. Trees with many holes cannot be used for veneer. The beetle holes remain visible for as long as 40 years.

Sometimes the beetle holes are infested by a scale insect, *Xylococculus betulae.* A sure sign of this is the white wax tube from the insect's anus, which protrudes as much as an inch out of the hole in the bark. Woodpeckers feed on these scale insects and thus keep the wounds open. Small bark flaps indicate woodpecker activity.

Seams and Frost Cracks

Seams and frost cracks may form on all northern hardwood species. Often they begin where the stem has already been weakened by mechanical wounds or branch stubs. Cracks that have evaginated lips indicate defects that penetrate the stem. Cracks without lips are often superficial. When trees have several cracks with lips, the defect pattern inside the tree may be star-shaped in cross-section; so it is impossible to saw high-quality boards from such trees. Fungus fruit bodies in cracks indicate decay.

Nectria Canker

Nectria canker, caused by the fungus *Nectria galligena,* may form on all the northern hardwood species.

The cankers commonly form about branch stubs. Discoloration is associated with the cankers; but the defect rarely goes more than a few inches above and below the canker. The bark falls from the stem, and hard white wood is exposed. Trees often break at the canker.

The canker itself is very hard and decay-resistant. *Fomes connatus* and *Poria obliqua* are sometimes found in the cankers. When *N. galligena* infects logging wounds, the defect is usually limited to a few inches above and below the wound. The fruit bodies are minute red lemon-shaped structures. You can find them (with a hand lens) in the bark cracks between dead and living bark.

Eutypella Canker

This kind of canker, caused by the fungus *Eutypella parasitica,* is found on maples. These cankers are sometimes called "cobra cankers" because the tree stem becomes flattened and bends back somewhat like a cobra about to strike. Though the canker occurs on young trees, it takes the cobra form only on older trees. The fungus commonly infects branch stubs. The defect is limited to several inches above and below the canker. The fruit bodies of the fungus are minute black forms with necks up to 1/4 inch long.

Burls and Swollen Stems

Burls and swollen stems occur on all the northern hardwoods. The fusiform (spindle-shaped) swollen areas on maples and birches are probably different from the common burl. No wood is exposed on the swollen areas. But here the bark is very corky, and you often may find frass from bark-mining insects on this corky bark. Some fusiform swellings may be due to fungi infecting the outer bark.

Defect from burls is usually limited to the area of the burl or swelling. The discolorations are brown-red to green in maples, and bright orange-red in birches. Wavy grain may form in the stem. When an ooze flows from the swollen part, the discoloration is advanced, and may extend 4 to 6 feet above and below the swelling. This advanced defect is most common on yellow birch.

Fire Wounds

Fire wounds are not common in northern hardwood forests, but you may find some on mature trees along old railroad lines. The wounds are bell-shaped, and always at the base of the tree. Such wounds are usually associated with serious decay. On mature trees with well-healed stubs, the decay may extend 4 to 6 feet above the wound. On old trees with large open stubs the decay may extend as much as 12 feet above the wound.

Beech Bark Disease

Beech bark disease is caused by Nectria fungi—especially *Nectria coccinea* var. *faginata*—that infect bark wounds made by the scale insect *Cryptococcus fagi.* The disease may kill small areas

on the stem, though the bark remains smooth. Smetimes a callus ridge forms to wall off the dead spots; and little defect results. But trees heavily infested by the insect and then infected by the fungus are killed. Such trees should be salvaged as soon as possible.

Secondary decay organisms are quick to attack trees that have beech bark disease. *Hypoxylon* species, *Fomes fomentarius,* and others invade the wood beneath the bark. Fruit bodies on the dead bark indicate decay. Check for *Hypoxylon* species first.

Cankers caused by another scale insect, *Xylococculus betulae,* may follow the onset of beech bark disease. These cankers have a slit through the center. A white wax tube ½ to 1 inch long, which protrudes from the insect, is a sure sign of the presence of this scale insect. An individual canker causes little defect, but many of them together cause serious damage.

Bleeding Cankers

Bleeding cankers can be found on all northern hardwood species. On birches and beech, the oozing liquid is red to red-tan; on maples it is black. The wet spots in the bark are associated with dead areas on the stem. These may be small spots less than 1 inch in diameter; or they may be long strips extending several feet from dead roots far up the stem. Bleeding spots are most common directly below branches.

Isolated bleeding spots may indicate insect injury, or they may indicate an early stage of canker formation. On birches, check bleeding spots for ambrosia beetle injury.

Stem Borers

The stem borer *Xylotrechus aceris* attacks young red maple trees, usually near a branch stub. The wound looks like a small sugar maple borer wound. Dark moist discoloration and decay are associated with the wounds, and several infestations can cause serious injury to young trees. Infested trees should be cut in early weedings.

Many other stem-boring insects attack northern hardwood trees, mostly those trees already weakened by other agents. One example is the bronze birch borer *(Agrilus anxius),* which attacks the trees

injured in logging; and the pigeon tremex *(Tremex columba),* which attacks beech trees weakened by beech bark disease. Wounds by these insects initiate the discoloration and decay processes; and trees injured by these insects should be harvested as soon as possible.

In general, if you see signs of attack by stem-boring insects, look for some other primary cause of injury to the tree.

Sunscald

Sunscald may occur when tree bark that has been shaded all its life is suddenly exposed to long periods of full sunlight. This happens when trees are exposed by windthrow or logging operations. The bark is often killed and falls away, leaving a wound face that is usually bright white and dry. Discoloration processes begin as soon as the bark dies, but little defect results. However, insects may infest the wounds, and sometimes woodpeckers drill for these insects and wound the surface enough to begin discoloration and decay processes. Sunscald does not injure large trees much, but may severely injure young trees with thin bark.

Hypoxylon Species

Hypoxylon species are among the most aggressive fungi that infect wounds recently inflicted. They may cause cankers and injure all northern hardwood species in various ways. However, the *Hypoxylon* cankers are not common. On maples, a target-shaped canker forms about branch stubs. The red-brown mounds of fungus tissue that contain the fruit bodies can be found on the canker face. The mounds, 1/8 to 1/4 inch in diameter and jet black inside, may occur in clusters. The common result is a dull red and white mottled discoloration and decay 1 to 2 feet above and below the canker.

The coal fungus, *Hypoxylon deustum (Ustulina vulgaris),* causes a white rot in the lower parts of maples and beech. The fungus tissues that contain the fruit bodies are black and crusty, resembling coal. In wounds on overmature trees, this fungus may cause decay 1 to 3 feet above the wound. The coal fungus is common on old stumps, which look like black burned wood. The

decayed wood due to the coal fungus has many black zone lines.

Hypoxylon species also injure the tops of suppressed young beech trees. Once established in a dead leader, the fungus grows slowly down the main stem. This kind of injury is common in thick stands of young beech under heavy shade. The result is a dull red and white discoloration and decay.

RECOMMENDATIONS

From what we know now about the patterns of discoloration and decay in the wood of living northern hardwood trees and about the external signals of this decay and discoloration, we can offer some recommendations. Our recommendations are aimed to asnwer two questions: What can we do to assure future crops of high-quality trees? And how can we make the most of what we now have?

We do not mean to say that this is the last word on the subject. We do not have all the answers now. But we are continuing our research on this subject, and we hope to use whatever new knowledge we acquire to further clarify and refine our present concepts. Meanwhile, the knowledge we have now can be put to some practical use.

General

First, learn to recognize the external signs of defect in the wood of the living tree, and to understand the processes of discoloration and decay. This is suggested as an aid to making decisions about treatment of the individual tree and the forest stand.

Do not overestimate the amount of defect in northern hardwood trees. This is easy to do. As you have seen, northern hardwood trees have a way of sealing off their defects and limiting them to certain areas so that clear new wood can grow, unaffected by earlier defects. Some wounds that look very bad do little damage to the wood.

Bear in mind that time is important: the most serious wounds cause little damage in a short time; decay takes time. If you can

tell the age of the wound—dates of past logging jobs might be helpful—this might help you estimate the severity of the damage.

Mature Trees

Carefully evaluate all the external signs of discoloration and decay to make the most reliable possible estimate of the wood quality in the tree, and the pattern of the decay and discoloration. Watch especially for poorly healed stubs, on all species.

Again, do not overestimate the amount of decay. In the northern hardwoods, decay columns end abruptly. Columns of discoloration and decay advance up and down the stem, as time passes, but they do not spread outward into the new wood formed after the tree was injured.

Put each tree to the best use that its pattern of discoloration and decay allows. Be cautious in selecting trees for high-quality uses such as veneer if there are signs of many small damaging defects such as injuries by ambrosia beetles, sugar maple borers, cambium miner galleries, and sapsucker holes.

Sprout Clumps

From sprout clumps, select for crop trees the one or two dominant stems that have well-healed small stubs. Do not consider using clumps whose stems all have many poorly healed stubs.

Young Trees

In selecting young trees to favor for future growth as crop trees, select those that have lost their lower branches and have healed branch-stub wounds.

Use silvicultural practices to grow trees that are tall and slender with well-developed crowns, and whose branches below the 16-foot height are few and small.

Do not select for crop trees those that have any cankers, sugar maple borer injury, or large cracks at the base. Above all, do not select those that have many large unhealed branch-stub wounds.

Differentiate carefully between those signs of discoloration and decay that may look serious but do not indicate poor vigor—such as mechanical wounds—and those that do indicate poor vigor—such as unhealed stubs. Favor trees of good vigor.

Pruning

The purpose of pruning should not be to prevent all defect, but rather *to limit* defect to a small central core. Much past emphasis has been put on how to prune without causing discoloration and decay. This may be impossible: some discoloration and decay cannot be avoided. The question is rather: how much central defect can a log have and still contain a large volume of high-quality wood?

So if you want to limit the defects in trees to a central core less than 4 inches in diameter, then treat the trees when they are 4 inches in diameter. How treat them? Prune those you want to keep, and cut the rest.

Which trees should be pruned? Certainly not all trees, for pruning takes time and costs money. Select for pruning those trees that have few low heavy branches, and have healed their branch stubs well. Do not waste time and money on trees that show signs of poor stub healing.

Prune to make good trees into better ones. But economically it is not yet good practice to try to make poor trees into good ones.

The Stand

High-quality trees tend to occur in groups; and so do low-quality trees. So consider not only the individual tree, but also the stand.

Consider the species in the stand. One area seldom supports good growth of all the species. And on some areas, trees simply do not grow well. For example, mountain tops are no place for birch: tops break, and Nectria cankers abound.

In looking at a particular species in a stand, look at the whole group of trees of that species for a sign of defect that can be recognized easily. Determine how common that defect is among that species in that stand. For example, sugar maple borer wounds often occur in groups of trees. If you find them on one tree, you may easily find them on 50 more. The same applies for swollen knots on red maple, galls on yellow birch, and collar cracks on paper birch. This is often called the "cluster effect."

Where you find a cluster of individuals that have signs of the same defect, evaluate those trees for the pattern of discoloration and decay in their wood. Then you can decide what to do with those trees.

Also, in areas where diseases have killed or deformed many of the trees, do not cut the few trees that have remained healthy and vigorous and have healed their wounds well. These may be the genetically resistant trees that are needed for seed to regenerate better stands for the future.

■

For Additional Information —

see Shigo, Alex L., SUCCESSION OF ORGANISMS IN DISCOLORATION AND DECAY OF WOOD: International Review of Forestry Research II: 237-299. Academic Press, New York, 1967. This publication lists 300 literature references on this subject.

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THE FOREST SERVICE of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

TREES and SHRUBS

Penobscot County, Maine

CLEMSON UNIVERSITY
NOV 3 1970

by Lawrence O. Safford
Robert M. Frank
Elbert L. Little, Jr.

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

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COVER PHOTO: Chemo Pond as seen from the boat landing on the Penobscot Experimental Forest.

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A spruce-fir forest of Maine, typical of the Penobscot Experimental Forest.

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THE PENOBSCOT Experimental Forest, a research unit of the Northeastern Forest Experiment Station, is located in southern Penobscot County, Maine. This record of the Penobscot Forest and its vegetation has been prepared as a reference aid for the forest researcher, the student, and the visitor to the Forest.

In this booklet you will find a brief description of the Forest, its history and physical features, and a list of the trees and shrubs found on the Forest. A list of publications about research on the Forest is appended.

We have found and identified 103 species of woody plants and shrubs on the Penobscot Forest, of which 5 are exotic introductions. The list includes 41 trees, 60 shrubs, and 2 woody vines.

HISTORY AND MANAGEMENT

The Penobscot Experimental Forest consists of 4,000 acres (6¼ square miles) of woodland located about 8 miles northeast of Bangor, in the towns of Bradley and Eddington. This land was purchased in 1950 by nine large land-owning companies, and was leased to the Northeastern Forest Experiment Station of the Forest Service, U. S. Department of Agriculture, for 99 years.

This was the first time in the history of American forestry that private wood-using industries cooperatively purchased land to be leased to the Federal Government for research purposes. The companies that took part in this unique project are Dead River Company, Eastern Corporation (now a Division of Standard Packaging Corporation), Great Northern Paper Company, Hollingsworth and Whitney Company (now Scott Paper Company), International Paper Company, Oxford Paper Company (now Ethel Corporation), Penobscot Development Company (now a part of Diamond International Corporation), S. D. Warren Paper Company (now Scott Paper Company), and St. Regis Paper Company.

On this Forest the Northeastern Forest Experiment Station conducts research in spruce-fir silviculture. The Station's research unit here, headquartered at Orono, is responsible for planning,

establishing, and maintaining research studies on the area as well as administering logging operations and maintenance of roads and boundaries.

A three-man operating committee represents the landowners in the administration of the area. This operating committee receives stumpage fees from the sale of timber cut during the silvicultural experiments and fees from the leasing of several camp lots. These fees are deposited into a fund that is used primarily for paying property taxes on the land. The fund has also been used to acquire additional land, to help finance a research project, and to carry out timber-stand-improvement work.

Each of the landowners is also represented on the Orono unit's Forestry Research Advisory Committee. This committee meets annually and helps keep open lines of communication between the landowners and the research scientists. Progress and results of studies are quickly passed on to the landowners, and the need for new research work is conveyed to the scientists.

The Penobscot Forest is also used by others on a cooperative basis. The Maine Department of Inland Fisheries and Game is conducting several studies on the Forest, including a large-scale study of the quantity and quality of food and cover provided by different cutting methods. Forest pathologists from the Station's laboratory at Hamden, Connecticut, are studying the rate of spread of decay-causing fungi in the principal softwood and hardwood species. The Station's geneticists have installed one replication of their regional white pine provenance study on the Forest and have outplanted specimens of a number of exotic species and hybrid pine and spruce, a list of which is included as an appendix. And students from the University of Maine also conduct research projects on the Forest.

Only a very small portion of land within the Forest was ever cleared for agriculture or grazing. Most of the area was cut lightly in the recent past (30 to 50 years) for pine, hemlock, and spruce sawlogs. Earlier cutting may have been heavier. Presence of charcoal and old burned stumps in many areas indicates that fires followed the cutting of pine stands.

The present stands are 75 to 110 years old. In some areas two-storied stands are developing — an understory of fir and some spruce beneath old stands of other species. Approximately 1,000 acres (25 percent of the total forest area) have been subjected to silvicultural cutting, ranging from clearcut harvesting to intensive selection cutting.

A 39-acre area on the eastern side of Blackman Stream has been designated as a natural area where no cutting will be done. This area is divided approximately in half into an upland type consisting of a dense stand of balsam fir, white pine, red spruce, and eastern hemlock on glacial till soils, and a swamp type consisting of an open stand of red and black spruce, white pine, and tamarack on organic soils. The remainder of the forest is available for new research studies.

A spruce-hemlock stand on the Penobscot Forest. This stand is being managed to favor red spruce over hemlock and balsam fir.

Topography

Located east of the Penobscot River, the Penobscot Experimental Forest lies in an area of transition between the Central Uplands and the Coastal Lowlands *(Toppan 1935)*. The relief is slight, ranging in elevation from 80 to 250 feet above sea level. The land is imperfectly drained by intermittent brooks and streams. Most of the eastern boundary of the forest is formed by 1, 200-acre Chemo Pond and its outlet, Blackman Stream.

Climate

The climate of the area is cool and humid. Thirty-year records of the weather station at the Old Town Airport, 8 miles northwest of the Experimental Forest, show an average annual temperature of 44.3° F. and average annual precipitation of 40.6 inches. Growing degree-days, cumulative to the base 40° F., total 4,000 for the entire year and 3,000 for the period 1 March to 26 September *(Deither and Vittum 1963)*. Average length of the freeze-free period is 144 days at the Old Town weather station *(Havens and McGuire 1961)*. The Forest is near the line between Plant Hardiness Zones 4 and 5, which has average annual minimum temperatures of −20° F. *(U. S. Natl. Arboretum 1965)*.

Soils

Soils of the Experimental Forest have been strongly influenced by the glacial history of the region. Wisconsin glacial till derived from fine-grained, dark-colored sedimentary rock (slates and shales) forms the principal parent material. Major soil types occurring on the glacial till ridges are well-drained Plaisted loams and stony loams, and moderately well-drained Howland loams and sandy loams. Flat till areas between the ridges are occupied by the poorly and very poorly drained Monarda and Burnham loams and silt loams. Outcroppings of vertically bedded shale covered by a thin mantle of till represent the Thorndike stony and very stony loams.

Some of the lowest areas along the present watercourses and in depressions are occupied by deposits of lacustrine and marine fine sediments. Common soil types on these parent materials include moderately well drained Buxton silt loam, poorly drained Scantic silt loam and very poorly drained Biddeford silt loam and silty clay loam.

A treeless flood plain consisting of recent alluvium, which is subject to annual floods, occurs along Blackman Stream. Soil types here are the very poorly drained Saco silt loams and fine sandy loams.

Glacio-fluvial sands and gravels are limited to a small esker system along Blackman Stream at the northeastern edge of the Forest. Soils on these materials are the excessively drained Stetson gravelly sandy loam, well-drained Stetson fine sandy loam, and well-drained Machias fine sandy loam.

A few organic deposits of muck and peat occur, but all are forested. There are no treeless heaths or muskegs.

Forest Types

The Penobscot Experimental Forest is located in an area of transition between the transition hardwoods-white pine-hemlock and the spruce-fir-northern hardwoods forest types as described by Westveld et al. *(1955)*. Softwood stands composed primarily of balsam fir, red spruce, and white spruce occupy the low-lying imperfectly drained areas. In areas of better drainage, softwood stands have a high proportion of eastern hemlock, with some white pine. White pine and red spruce, along with occasional red pine, predominate in softwood stands on the shallow well-drained soils. Paper birch and red maple are present in small numbers in nearly all the softwood stands.

Hardwood stands composed of sugar maple, beech, and yellow birch occupy the highest elevations of well-drained glacial till soils. Hardwood stands on areas of very poor drainage and organic soils are composed of red maple, American elm, and black ash. Many of these stands are associated with softwood stands composed of black spruce or northern white-cedar and occasional tamarack.

Mixed softwood-hardwood stands occur on all the intermediate soil drainage sites. Red maple and paper birch are the principal hardwood associates of spruce, fir, hemlock, and pine. Big-tooth and quaking aspens occur in some areas, and so does red oak.

THE TREES AND SHRUBS

The collection of herbarium specimens from which the list of trees and shrubs was compiled was made by the Penobscot Experimental Forest staff and Elbert L. Little, Jr., in 1967 and 1968. The identifications have been checked by Dr. Little. Several specimens were further determined by Richard J. Eaton, Curator of Vascular Plants, New England Botanical Club.

Duplicate sets of about 150 numbers of specimens have been deposited in the Forest Service Herbarium at Washington, D. C.; the Forest Service spruce-fir silviculture project at Orono, Maine; and the Herbarium of the University of Maine, Orono, Maine. An incomplete set has been deposited in the Herbarium of the University of New Hampshire, Durham, New Hampshire.

Woody plants growing naturally on the Penobscot Experimental Forest, as listed here, total 103 species in 60 genera and 26 plant families. However, these figures include five introduced species (four genera and three families): *Berberis thunbergii, Malus pumila, Rhamnus frangula, Solanum dulcamara,* and *Lonicera xylosteum.* Also mentioned but not counted in the totals are two species of herbs in woody plant genera: *Aralia racemosa* and *Cornus canadensis.*

The four largest plant families together contain more than one-half the genera (30) and species (54), as follows: Rosaceae, 9 genera and 20 species (including 1 genus and 2 introduced species); Ericaceae, 9 genera and 13 species; Caprifoliaceae, 5 genera and 11 species (1 introduced); and Pinaceae, 7 genera and 10 species. The largest genera are *Rubus* with 6 species, *Acer* and *Salix* with 5 each, and *Cornus, Vaccinium,* and *Viburnum* with 4 each.

The list of woody plants is thought to be nearly complete for the Penobscot Experimental Forest. However, a few rare species

may remain to be collected later. Some others were recorded for southern Penobscot County by Hyland and Steinmetz *(1944)* and in the check list by Ogden, Steinmetz, and Hyland *(1948).*

No unusual records or range extensions were found, nor were any expected. All but one of the woody plant species found on the Experimental Forest were recorded in Penobscot County (or reported under another name) in the check list by Ogden, Steinmetz, and Hyland *(1948).* The addition is an introduced cultivated ornamental, apparently an escape, *Lonicera xylosteum.*

In growth form, 41 species are trees (small, medium, or large), and 60 are shrubs (large and small and subshrubs). Only 2 species are woody vines: *Parthenocissus quinquefolia* and *Solanum dulcamara,* the latter introduced. Classed with the shrubs is one minute parasitic epiphyte: dwarf-mistletoe, *Arceuthobium pusillum.* A few species of creeping plants are barely woody; for example, *Gaultheria hispidula, Michella repens,* and *Linnaea borealis.*

Of the 41 tree species, most are small (including large shrubs attaining tree size) or of medium size. Only 13 species are classed as becoming large trees on the Penobscot Experimental Forest, as follows: *Picea glauca, Picea rubens, Pinus resinosa, Pinus strobus, Tsuga canadensis, Betula alleghaniensis, Betula papyrifera, Fagus grandifolia, Quercus rubra, Ulmus americana, Acer saccharum, Tilia americana, Fraxinus americana.*

The relatively large number of small shrub species and the small number of large trees are to be expected in Maine. Northward into cooler climates, the growth forms of native woody species become smaller.

Certain families of woody plants in the eastern United States are absent on the Forest, though they may be found in southern or coastal parts of Maine or may be represented in cultivation. Examples are Juglandaceae, walnut family; Magnoliaceae, magnolia family; Lauraceae, laurel family; and Leguminosae, legume family (native species all herbaceous). Certain tree genera are absent; for example, *Celtis, Morus, Liquidambar, Platanus,* and *Nyssa.* On the Experimental Forest three tree genera have only one native species: *Quercus, Ulmus,* and *Crataegus.*

In the following list of the trees and shrubs growing naturally on the Penobscot Experimental Forest, scientific names and common names of trees are those accepted in the U. S. Forest Service check list *(Little 1953)*. The trees are further described and illustrated in publications on Maine trees by Stark, LaBonte, and Nash *(1968)* and Hyland *(1964)*. Scientific names of shrubs are from Gleason *(1952)*, except the blackberries *(Rubus subg. Eubatus)*, which are from Hodgdon and Steele *(1966)*. Varieties have not been distinguished. However, commonly used varietal names and synonyms have been inserted in parenthesis. Additional locally used common names are included for some species.

Each species in the list is accompanied by a description containing the following information.

Size and Character

- Large tree: taller than 70 feet and 24 inches d.b.h. or larger.
- Medium tree: 30 to 70 feet tall and 12 to 24 inches d.b.h.
- Small tree: less than 30 feet tall and less than 12 inches d.b.h.
- Large shrub: taller than 5 feet but not qualifying as a tree.
- Small shrub: shorter than 5 feet, often only 1 to 2 feet tall or less.
- Subshrub: creeping or trailing species, often barely woody.
- Woody vine: twining or climbing woody plant.

Occurrence

- Where the species is found on the Penobscot Experimental Forest: forest type—softwood, mixedwood, hardwood—roadsides, openings, or general.

General Habitat

- Soil and site conditions where the species is found, after Hyland and Steinmetz *(1944)*.

Abundance

- Frequency of occurrence on the Penobscot Experimental Forest: abundant, common, uncommon, or rare.

TAXACEAE : YEW FAMILY

Taxus canadensis Marsh. **Canada yew**
Small shrub; softwood type; moist soils in shade of conifers; uncommon. Local common name: ground hemlock.

PINACEAE : PINE FAMILY

Abies balsamea (L.) Mill. **balsam fir**
Medium tree; general; abundant. Common forest tree, forms large part of stand on low-lying wet soils and is associated with spruce and hardwood species on upland soils.

Juniperus communis L. (var. *depressa* Pursh) **common juniper**
Small shrub; open places; dry, shallow, or sandy soils; rare. Common and locally a problem in pastures in some areas of the State.

Larix laricina (Du Roi) K. Koch **tamarack**
Medium tree; softwood type; swamps and boggy places, sometimes in wet abandoned pastures; common. Other common names: hackmatack, eastern larch, juniper.

Picea glauca (Moench) Voss **white spruce**
Medium to large tree; general; often in moist habitats with red spruce; common. Colonizes abandoned fields and pastures. Local common name: cat spruce.

Picea mariana (Mill.) B.S.P. **black spruce**
Medium tree; softwood types; chiefly in bogs or organic soils, also on adjacent uplands; common.

Picea rubens Sarg. **red spruce**
Medium to large tree; general; mostly on uplaid soils and shallow rocky soils; abundant.

Pinus resinosa Ait. **red pine**

Medium to large tree; softwood type; on dry sites of sandy or gravelly soils and very shallow soils; uncommon. Local common name: Norway pine.

Pinus strobus L. **eastern white pine**

Large tree; general; mostly on fertile well-drained soils or shallow soils, also occasionally found in wet areas; abundant. Other common names: northern white pine, pumpkin pine, soft pine. Colonizes abandoned agricultural land.

Thuja occidentalis L. **northern white-cedar**

Medium tree; softwood stands; swamps and other moist habitats; abundant. Other common names: eastern arborvitae, eastern white-cedar.

Tsuga canadensis (L.) Carr. **eastern hemlock**

Large tree; softwood and mixedwood types; uplands and well-drained soils; abundant.

SALICACEAE : WILLOW FAMILY

Populus balsamifera L. **balsam poplar**

Medium tree; hardwood type; open areas; uncommon. Locally called balm-of-Gilead poplar.

Populus grandidentata Michx. **bigtooth aspen**

Medium tree; hardwood or mixedwood type; pioneer species of rich soils; common. Locally called popple.

Populus tremuloides Michx. **quaking aspen**

Medium tree; hardwood or mixedwood type; pioneer species, often on slightly drier and sandier soils than above *Populus* species; common. Locally called popple or trembling aspen.

Salix bebbiana Sarg. **Bebb willow**

Large shrub or small tree; open areas and roadsides, moist or dry soil; common.

Salix discolor Mühl. **pussy willow**

Large shrub; open areas, wet meadows, and boggy stream margins or dry sandy areas; uncommon.

Salix lucida Mühl. **shining willow**

Large shrub; open areas, banks of streams and ponds, often growing in water; common.

Salix pedicellaris Pursh (var. *hypoglauca* Fern.) **bog willow**

Small shrub, open areas, wet meadows and boggy stream margins; uncommon.

Salix sericea Marsh. **silky willow**

Large shrub; open areas; wet places and swamps along streams and flood plains; common.

MYRICACEAE : WAXMYRTLE FAMILY

Comptonia peregrina (L.) Coult. *sweetfern*

Small shrub; large openings; dry soils; abundant.

Myrica gale L. *sweetgale*

Small shrub; open areas; wet areas, bogs, and swamps; common.

BETULACEAE : BIRCH FAMILY

Alnus rugosa (Du Roi) Spreng. (*A. incana* auth.) **speckled alder**

Large shrub to small tree; open areas and roadsides; wet places along streams and moist soils; abundant.

Betula alleghaniensis Britton (*B. lutea* Michx. f.) **yellow birch**

Medium to large tree; hardwood type; rich moist soil; common.

Betula papyrifera Marsh. **paper birch**

Medium to large tree; hardwood and mixedwood types; general; abundant. Locally called white birch or canoe birch.

Betula populifolia Marsh. **gray birch**
Small tree; open areas; poor sandy or rocky soil; abundant. Pioneer species often invades old fields and pastures especially where soil is wet. Locally called poverty birch or Getchell birch.

Corylus cornuta Marsh. **beaked hazel**
Large shrub; small openings; generally on the poorer soils; common.

Ostrya virginiana (Mill.) K. Koch **eastern hophornbeam**
Small tree; hardwood types; rich woods; common. Locally called ironwood, leverwood, or hornbeam.

FAGACEAE : BEECH FAMILY

Fagus grandifolia Ehrh. **American beech**
Medium to large tree; hardwood types; rich moist soils; common.

Quercus rubra L. (*Q. borealis* Michx. f.) **northern red oak**
Medium to large tree; hardwood or mixedwood types; dry or moist soil, often in rocky places; common.

ULMACEAE : ELM FAMILY

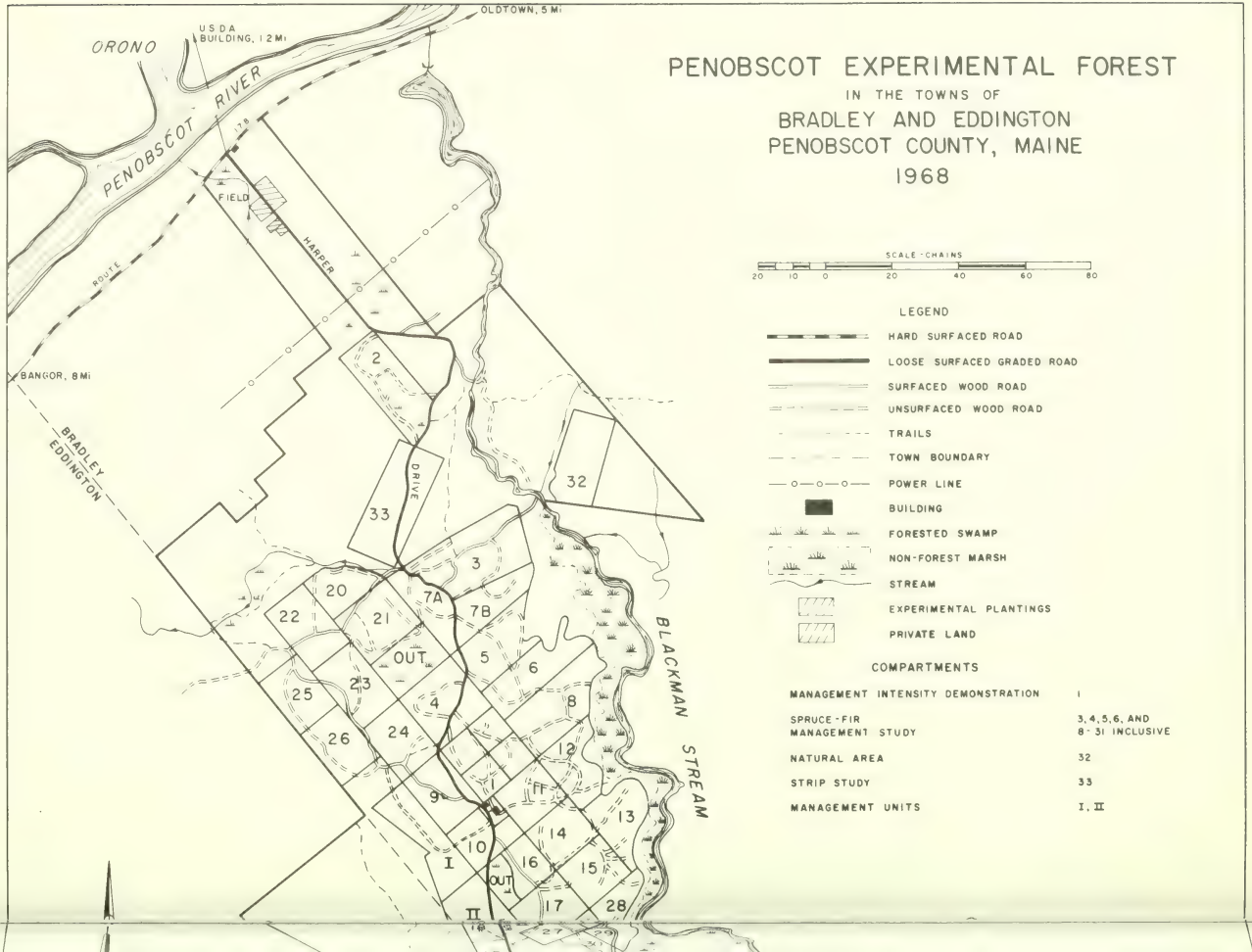
Ulmus americana L. **American elm**
Large tree; hardwood type; rich moist soils along water courses; common.

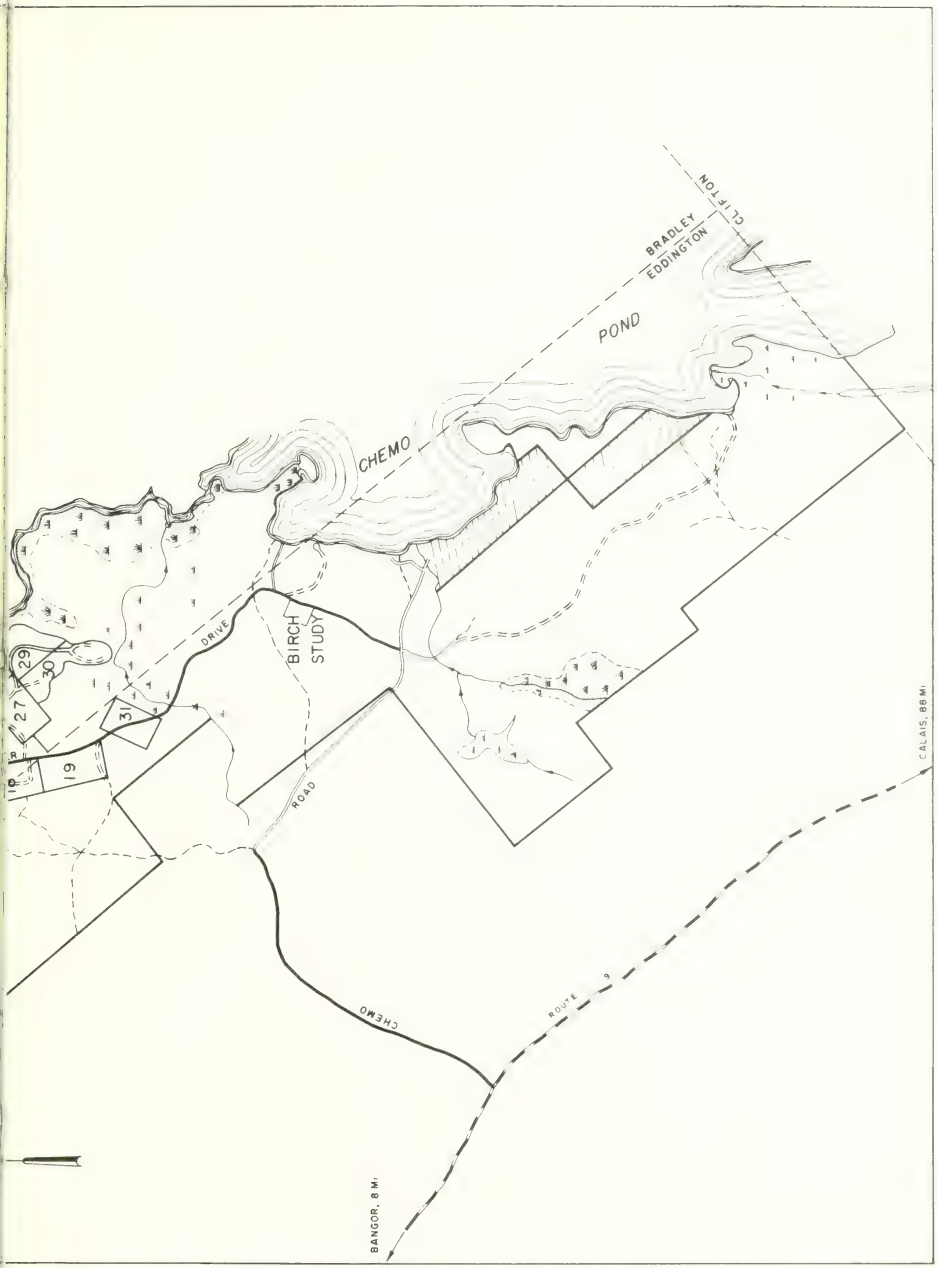
LORANTHACEAE : MISTLETOE FAMILY

Arceuthobium pusillum Peck **dwarf-mistletoe**
Subshrub; softwood type; occurs as parasite on crowns of black spruce; uncommon.

BERBERIDACEAE : BARBERRY FAMILY

Berberis thunbergii DC. **Japanese barberry**
Small shrub; open areas; rare; introduced, escaped from cultivation.


PENOBSCOT EXPERIMENTAL FOREST
IN THE TOWNS OF
BRADLEY AND EDDINGTON
PENOBSCOT COUNTY, MAINE
1968
ORONO
U.S.D.A. BUILDING, 1.2 Mi
OLDTOWN, 5 Mi
PENOBSCOT RIVER
FIELD
HARVEY
ROUTE
BANGOR, 8 Mi
BRADLEY
EDDINGTON
DRIVE
BLACKMAN STREAM
OUT
FF
I
II
SCALE - CHAINS
20 10 0 20 40 60 80
LEGEND
HARD SURFACED ROAD
LOOSE SURFACED GRADED ROAD
SURFACED WOOD ROAD
UNSURFACED WOOD ROAD
TRAILS
TOWN BOUNDARY
POWER LINE
BUILDING
FORESTED SWAMP
NON-FOREST MARSH
STREAM
EXPERIMENTAL PLANTINGS
PRIVATE LAND
COMPARTMENTS
MANAGEMENT INTENSITY DEMONSTRATION 1
SPRUCE-FIR MANAGEMENT STUDY 3, 4, 5, 6, AND 8-31 INCLUSIVE
NATURAL AREA 32
STRIP STUDY 33
MANAGEMENT UNITS I, II


BRADLEY
EDDINGTON
CLIFTON
POND
CHEMO
DRIVE
BIRCH
STUDY
ROAD
CHEMO
ROUTE 9
BANGOR, 8 Mi
CALAIS, 88 Mi
T6 R2
27
29
30
31
19

SAXIFRAGACEAE : SAXIFRAGE FAMILY

Ribes hirtellum Michx. **wild gooseberry**

Small shrub; small open areas; swamps and grassy swales; uncommon.

HAMAMELIDACEAE : WITCH-HAZEL FAMILY

Hamamelis virginiana L. **witch-hazel**

Large shrub to small tree; small openings; moist or dry often rocky woods; common.

ROSACEAE : ROSE FAMILY

Amelanchier arborea (Michx. f.) Fern. **downy serviceberry**

Large shrub; roadside, near Rt. 178; uncommon.

Amelanchier laevis Wieg. **Allegheny serviceberry**

Small tree; openings and roadsides; acid soils damp or dry; common. Locally called shadbush.

Aronia melanocarpa (Michx.) Ell. (*Pyrus melanocarpa* (Michx.) Willd.) **black chokeberry**

Large shrub; open areas; moist soils or rocky barrens; uncommon.

Crataegus macrosperma Ashe (?) **hawthorn**

Large shrub or small tree; openings; dry rocky soil; common. Specimens sterile, and identification uncertain.

Malus pumila Mill. (*Pyrus malus* L.) **apple**

Small tree; openings, old pasture; common; introduced, escaped from cultivation.

Prunus pensylvanica L. f. **pin cherry**

Small tree; open areas; recent openings following fire; common. Also called fire cherry, wild red, or bird cherry.

Prunus serotina Ehrh. **black cherry**

Medium tree; hardwood type; rich moist soils; uncommon.

Prunus virginiana L. **common chokecherry**
Large shrub or small tree; openings, edges of clearings; rich soil; uncommon.

Rosa johannensis Fern. **rose**
Small shrub; roadside and open areas; uncommon.

Rosa palustris Marsh. **swamp rose**
Small shrub; opening along Blackman Stream; wet swampy soil; uncommon.

Rosa virginiana Mill. **Virginia rose**
Small shrub; roadside and openings; uncommon.

Rubus allegheniensis Porter **common blackberry**
Small to large shrub; roadside and openings; dry soils; common.

Rubus hispidus L. **swamp dewberry**
Small shrub; forming dense tangle along ground; common.

Rubus pensilvanicus Poir. (*R. ostryifolius* Rydb.) **blackberry**
Small shrub; open areas and fields; uncommon.

Rubus pubescens Raf. **dwarf red blackberry**
Small shrub; fields and open areas; moist soils; common.

Rubus strigosus Michx. (*R. idaeus* L. var. *strigosus* (Michx.) Maxim.) **red raspberry**
Small shrub; open areas and roadsides; dry or moist soils; common.

Rubus vermontanus Blanch. (?) **blackberry**
Small shrub; open areas and roadsides; dry or moist soils; common.

Sorbus americana Marsh. (*Pyrus americana* (Marsh.) DC.) **American mountain-ash**
Small tree; open areas and roadsides; moist or dry soil; uncommon.

Spiraea latifolia (Ait.) Borkh. **meadowsweet**

Small shrub; fields and open places; rocky poor soil, moist or dry; abundant.

Spiraea tomentosa L. **hardhack**

Small shrub; fields and open places; rocky poor soil, moist or dry; common. Locally called steeplebush.

ANACARDIACEAE : CASHEW FAMILY

Rhus radicans L. (var. *rydbergii* (Small) Rehd.; *Toxicondendron radicans* (L.) Kuntze) ***poison-ivy***

Small shrub; hardwood type; along stream banks and roadsides, wet to dry soils; common. A few varieties and forms have been recognized.

Rhus typhina L. **staghorn sumac**

Large shrub or small tree; open areas; usually dry soils and rocky places; common.

AQUIFOLIACEAE : HOLLY FAMILY

Ilex verticillata (L.) Gray **winterberry**

Small to large shrub; hardwood type; open wet places, wet soils of hardwood swamps; common. A few varieties have been distinguished.

Nemopanthus mucronata (L.) Trel. **mountain-holly**

Large shrub or small tree; swamps, bogs, or wet places; uncommon.

ACERACEAE : MAPLE FAMILY

Acer pensylvanicum L. **striped maple**

Small tree (often shrubby); hardwood type; rich moist soil; common. Locally called moosewood.

Acer rubrum L. **red maple**

Medium tree; hardwood, mixedwood or softwood types; moist to wet soils and swamps; abundant. Locally called soft or white maple.

Acer saccharinum L. **silver maple**

Medium tree; hardwood type; banks of streams and lake shores; rare, along bank of Blackman Stream. Locally called white maple.

Acer saccharum Marsh. **sugar maple**

Large tree; hardwood type; deep, rich, well-drained soils; common. Other common names: hard or rock maple.

Acer spicatum Lam. **mountain maple**

Large shrub or small tree; hardwood or mixedwood types; cool moist soils; common.

RHAMNACEAE : BUCKTHORN FAMILY

Rhamnus frangula L. **glossy buckthorn**

Large shrub or small tree; one specimen found along Blackman Stream near old dam site; rare, introduced.

VITACEAE : GRAPE FAMILY

Parthenocissus quinquefolia (L.) Planch. **Virginia creeper**

Woody vine; hardwood type; moist soils, especially along streams and roads; rare.

TILIACEAE : LINDEN FAMILY

Tilia americana L. **American basswood**

Large tree; hardwood type; moist rich soils; uncommon.

THYMELAEACEAE : MEZEREUM FAMILY

Dirca palustris L. **leatherwood**

Large shrub; hardwod type; moist often calcareous soils; rare. Also called wicopy.

ARALIACEAE : GINSENG FAMILY

Aralia hispida Vent. **prickly sarsaparilla**

Subshrub; recent openings and burned areas; dry soils, rocky places; common.

Aralia nudicaulis L. **wild sarsaparilla**
Subshrub; under softwoods or hardwoods; moist or dry soil; abundant.

Aralia racemosa L. **spikenard**
Herb; rich moist woods; common.

CORNACEAE : DOGWOOD FAMILY

Cornus alternifolia L. f. **alternate-leaf dogwood**
Large shrub to small tree; hardwood and mixedwood type; dry rocky soils; common.

Cornus amomum Mill. **silky dogwood**
Large shrub; open places along water courses; uncommon.

Cornus canadensis L. **bunchberry**
Herb; general; abundant.

Cornus rugosa Lam. **roundleaf dogwood**
Large shrub; hardwood and mixedwood type; rich moist soil; common.

Cornus stolonifera Michx. **red osier dogwood**
Large shrub; openings; along water courses and wet places; common.

ERICACEAE : HEATH FAMILY

Andromeda glaucophylla Link **bog-rosemary**
Small shrub; bogs and swales; common.

Chamaedaphne calyculata (L.) Moench **leatherleaf**
Small shrub; open areas; bogs, swamps, and other wet places; common.

Epigaea repens L. (var. *glabrifolia* Fern.) **trailing-arbutus**
Subshrub; general; sandy rocky soils, moist or dry; common. Locally called mayflower.

Gaultheria hispidula (L.) Mühl. (*Chiogenes hispidula* (L.) Torr. & Gray) **creeping snowberry**
Subshrub; softwood or mixedwood type; peat bogs and mossy soils; common.

Gaultheria procumbens L. **wintergreen**
Subshrub; general; dry soils or humus-covered rocks; common. Also called checkerberry or teaberry.

Gaylussacia baccata (Wang.) K. Koch **black huckleberry**
Small shrub; softwood type; rocky woods; rare.

Kalmia angustifolia L. **lambkill**
Small shrub; openings; moist to wet soils; common.

Ledum groenlandicum Oeder **Labrador-tea**
Small shrub; bogs and wet places; uncommon.

Rhododendron canadense (L.) B.S.P. **rhodora**
Small shrub; open areas in swamps, bogs, or wet places; common.

Vaccinium angustifolium Ait. **blueberry**
Small shrub; open areas; dry soils; common. Locally called lowbush or low-sweet blueberry.

Vaccinium corymbosum L. **highbush blueberry**
Large shrub, open areas; swamps, bogs, and wet places; uncommon.

Vaccinium macrocarpon Ait. **large cranberry**
Subshrub; open bogs, and wet places; often in sphagnum moss; common.

Vaccinium myrtilloides Michx. (*V. canadense* Kalm) **blueberry**
Small shrub; open places; dry or moist soils; common.

OLEACEAE : OLIVE FAMILY

Fraxinus americana L. **white ash**

Medium to large tree; hardwood type; rich moist soils; common.

Fraxinus nigra Marsh. **black ash**

Small tree; hardwood type; swamps and wet places; common. Also called brown or basket ash.

Fraxinus pennsylvanica Marsh. **green ash**

Small tree; a single plant 10 feet high beside Harper Drive near Rt. 178, the only record; rare. Also found along banks of Penobscot River 1/4 mile away. Also called red ash.

SOLANACEAE : NIGHTSHADE FAMILY

Solanum dulcamara L. **bitter nightshade**

Climbing woody vine; a single plant beside Harper Drive near Rt. 178, the only record; rare, introduced.

RUBIACEAE : MADDER FAMILY

Cephalanthus occidentalis L. **common buttonbush**

Small to large shrub; open areas; along water courses, often in water; uncommon.

Mitchella repens L. **partridge-berry**

Subshrub; softwood type; dry soils; common.

CAPRIFOLIACEAE : HONEYSUCKLE FAMILY

Diervilla lonicera Mill. **bush-honeysuckle**

Small shrub; open areas; roadsides; dry rocky soil; common.

Linnaea borealis L. (var. *americana* (Forbes) Rehd.) **twinflower**

Subshrub; general; moist mossy soils; common.

Lonicera canadensis Marsh. **American fly honeysuckle**

Small shrub; general; moist soils; common.

Lonicera villosa (Michx.) R. & S. **mountain fly honeysuckle**
Small shrub; open areas; wet rocky soils; common.

Lonicera xylosteum L. **European fly honeysuckle**
Large shrub; open areas; rare, introduced.

Sambucus canadensis L. **American elder**
Small to large shrub; openings and roadsides; rich soils; common. Also called common or black-berried elder.

Sambucus pubens Michx. **scarlet elder**
Small to large shrub; openings and roadsides; rocky soils; common.

Viburnum acerifolium L. **mapleleaf viburnum**
Small to large shrub; softwood type; dry to moist soils; common.

Viburnum alnifolium Marsh. **hobble-bush**
Small to large shrub; hardwood type; moist rich soils; uncommon. Also called witch hobble.

Viburnum cassinoides L. **withe-rod**
Large shrub; open places; wet or dry soils; common. Often called wild raisin.

Viburnum recognitum Fern. (*V. dentatum* L. var. *lucidum* Ait.) **arrowwood**
Small to large shrub; general; in small openings and along water courses; wet or dry soils; common.

■

LITERATURE CITED

Deither, B. E., and M. T. Vittum.
1963. The Climate of the Northeast: Growing Degree Days. N. Y. State Agr. Exp. Sta. Bull. 801, 84 pp., illus.

Gleason, Henry A.
1952. The New Britton and Brown Illustrated Flora of the Northeastern United States and Adjacent Canada. New York Bot. Gard., New York. 3 vols. illus.

Havens, A. V., and J. K. McGuire.
1961. The Climate of the Northeast: Spring and Fall Low-Temperature Probabilities. N. J. Agr. Exp. Sta. Bull. 801, 32 pp., illus.

Hodgdon, A. R., and Frederic Steele.
1966. Rubus Subgenus Eubatus in New England, A. Conspectus. Rhodora 68: 474-513.

Hyland, Fay.
1964. Conifers of Maine, Native and Commonly Introduced. Maine Univ. Coop. Ext. Serv. Bull. 345 revised, 27 pp., illus.

Hyland, Fay, and
Ferdinand H. Steinmetz.
1944. The Woody Plants of Maine, Their Occurrence and Distribution. xix + 72 pp., illus. Univ. Maine Press, Orono, Maine.

Little, Elbert L., Jr.
1953. Check List of Native and Naturalized Trees of the United States (including Alaska). U. S. Dep. Agr. Handbook 41, 472 pp.

Ogden, E. C., F. H. Steinmetz, and
F. Hyland.
1948. Check List of the Vascular Plants of Maine. Josselyn Bot. Soc. Maine Bull. 8, 69 pp.

Stark, Douglas A., George A. LaBonte, and Robley W. Nash.
1968. Forest Trees of Maine. Maine Forestry Dep., Bull. 24, 93 pp., illus.

Toppan, Frederick W.
1935. The Physiography of Maine. J. Geol. 43: 76-87, illus.

United States National Arboretum.
1965. Plant Hardiness Zone Map. U. S. Dep. Agr. Misc. Pub. 814.

Westveld, Marinus, and others.
1956. Natural Forest Vegetation Zones of New England. J. Forestry 54: 332-338, illus.

■

Species Planted

Small numbers of specimens of the following exotic species and interspecific hybrids of spruce and pine have been planted in the Penobscot Experimental Forest. Data on location, numbers planted, and survival and growth are on file at the Orono office of the Northeastern Forest Experiment Station.

Picea abies (L.) Karst.
P. abies X *asperata*
P. abies X *koyamai*
P. abies X *montigena*
P. abies X *wilsonii*
P. asperata X *abies*
P. asperata X *montigena*
P. engelmannii Parry
P. engelmannii X *glauca*
P. glauca X *engelmannii*
P. glauca X *jezoensis*
P. glauca X *koyamai*
P. glauca X *pungens*
P. montigena X *abies*
P. montigena X *asperata*
P. omorika (Panic) Parkyne
P. omorika X *koyamai*
P. omorika X *orientalis*
P. orientalis (L.) Link
P. orientalis X *montigena*
P. orientalis X *omorika*
P. pungens Engelm.
Pinus ayacahuite X *strobus*
P. griffithii McClelland
P. griffithii X *strobus*
P. peuce X *strobus*
P. sylvestris X *densiflora*

Research Reports from the Penobscot Experimental Forest

Abbott, Herschel G., and Arthur C. Hart.
1961. MICE AND VOLES PREFER SPRUCE SEED. U.S.D.A. Forest Serv. NE. Forest Exp. Sta., Sta. Paper 153, 12 pp., illus.

Bjorkbom, John C.
1967. SEEDBED-PREPARATION METHODS FOR PAPER BIRCH. U.S.D.A. Forest Serv. Res. Paper NE-79, 15 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Bjorkbom, John C., and Robert M. Frank.
1968. SLASH BURNING AND WHOLE-TREE SKIDDING FAIL TO PROVIDE MINERAL-SOIL SEEDBEDS FOR SPRUCE-FIR. N. Logger and Timber Processer 16(7): 20, 45.

Bjorkbom, John C., David A. Marquis, and Frank E. Cunningham.
1965. THE VARIABILITY OF PAPER BIRCH SEED PRODUCTION, DISPERSAL, AND GERMINATION. U.S.D.A. Forest Serv. Res. Paper NE-41, 8 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Davis, Grant.
1958. GROWTH OF WHITE PINE AND RED SPRUCE TREES AFTER PRUNING. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 83, 2 pp.

Davis, Grant, and Arthur C. Hart.
1961. EFFECT OF SEEDBED PREPARATION ON NATURAL REPRODUCTION OF SPRUCE AND HEMLOCK UNDER DENSE SHADE. U.S.D.A. Forest Serv. NE. Forest Exp. Sta., Sta. Paper 160, 12 pp., illus.

Grisez, Ted J.
1954. 1954 HURRICANE DAMAGE ON PENOBSCOT EXPERIMENTAL FOREST. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 39, 2 pp.

Grisez, Ted J.
1954. RESULTS OF A MOUSE CENSUS IN A SPRUCE-FIR-HEMLOCK FOREST IN MAINE. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 28, 2 pp.

Hart, Arthur C.
1952. A WRIST GUARD FOR PULPWOOD HANDLERS. NE. Logger 1(5): 37, illus.

Hart, Arthur C.
1953. SMALL-FOREST MANAGEMENT IN THE SPRUCE-FIR REGION. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 21, 4 pp.

Hart, Arthur C.
1956. LOGGING ON THE PENOBSCOT EXPERIMENTAL FOREST. NE. Logger 5(6): 33, 90-91, illus.

Hart, Arthur C.
1956. RESULTS OF SMALL WOODLOT CUTTINGS ON PENOBSCOT EXPERIMENTAL FOREST, 1953 AND 1954. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 61, 2 pp.

Hart, Arthur C.
1958. PENOBSCOT WOODLANDS YIELD ANNUAL CUTS. U.S.D.A. Forest Serv. NE. Forest Exp. Sta. Forest Res. Note 84, 2 pp.

Hart, Arthur C.
1961. THINNING BALSAM FIR THICKETS WITH SOIL STERILANTS. U.S.D.A. Forest Serv. NE. Forest Exp. Sta., Sta. Paper 152, 8 pp.

Hart, Arthur C.
1964. THE PENOBSCOT MANAGEMENT-INTENSITY DEMONSTRATION PLOTS. U.S.D.A. Forest Serv. Res. Paper NE-25, 24 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Hart, Arthur C., Herschel G. Abbott, and Edward R. Ladd.
1968. DO SMALL MAMMALS AND BIRDS AFFECT REPRODUCTION OF SPRUCE AND FIR? U.S.D.A. Forest Serv. Res. Paper NE-110, 8 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Hart, Arthur C., and Lewis P. Bissell.
1959. FARM WOODLOTS: COST AND INCOME. Maine Agr. Ext. Serv. Circ. 338, 12 pp., illus.

Longwood, Franklin R.
1958. THE PENOBSCOT EXPERIMENTAL FOREST. NE. Forest Tree Improv. Conf. Proc. 5: 28-29.

McLintock, Thomas F.
1952. COST OF PRUNING RED SPRUCE IN NATURAL STANDS. J. Forestry 50: 485-486.

McLintock, Thomas F.
1954. THE PENOBSCOT EXPERIMENTAL FOREST. U.S.D.A. Forest Serv. NE. Forest Exp. Sta., 26 pp., illus.

McLintock, Thomas F.
1958. HARDPANS IN THE SPRUCE-FIR FORESTS OF MAINE. Soc. Amer. Foresters Proc. 1957: 65-66.

McLintock, Thomas F.
1959. A METHOD OF OBTAINING SOIL-SAMPLE VOLUMES IN STONY SOILS. J. Forestry 57: 832-834.

Mount, Peter, and William Gove.
1952. SITE INDEX FOR SPRUCE-FIR STANDS BASED ON AGE AT BREAST HEIGHT AND TOTAL HEIGHT. Univ. Maine Forestry Dep. Tech. Note 13, 3 pp., illus.

Northeastern Forest Experiment Station.
1960. PENOBSCOT EXPERIMENTAL FOREST. U.S.D.A. Forest Serv. NE. Forest Exp. Sta., 30 pp., illus.

Safford, Lawrence O., and Harold E. Young.
1968. NUTRIENT CONTENT OF THE CURRENT FOLIAGE OF RED SPRUCE GROWING ON THREE SOILS IN MAINE. Res. in the Life Sci., April 1968, pp. 27-31.

Schreiner, Ernst J.
1958. GENETIC IMPROVEMENT CONVERSION. NE. Forest Tree Improv. Conf. Proc. 5: 29-42, illus.

Wahlgren, Harold E., Arthur C. Hart, and Robert R. Maeglin.
1966. ESTIMATING TREE SPECIFIC GRAVITY OF MAINE CONIFERS. U.S.D.A. Forest Serv. Res. Paper FPL-61, 22 pp., illus. USDA. Forest Prod. Lab., Madison, Wis.

Wahlgren, Harold E., Gregory Baker, Robert R. Maeglin, and Arthur C. Hart.
1968. SURVEY OF SPECIFIC GRAVITY OF EIGHT MAINE CONIFERS. U.S.D.A. Forest Serv. Res. Paper FPL-95, 12 pp. U.S.D.A. Forest Prod. Lab., Madison, Wis.

Young, Harold E.
1954. FOREST SOILS-SITE INDEX STUDIES IN MAINE. Soil Sci. Soc. Amer. Proc. 18(1): 85-87.

■

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The Rate of Value Increase for Northern Red Oak, White Oak, and Chestnut Oak

by George R. Trimble, Jr.
and Joseph J. Mendel

U.S.D.A. FOREST SERVICE RESEARCH PAPER NE-129
1969

NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

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The Rate of Value Increase for Northern Red Oak, White Oak, and Chestnut Oak

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INTRODUCTION

MANAGERS of timber-growing enterprises, like other businessmen, need to establish sound economic bases for their decisions. One of these bases is financial maturity, the point at which trees cease to earn an adequate return and should be cut. We have developed financial maturity information for northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and chestnut oak (*Q. prinus* L.), based on tree-growth and tree-quality data collected in West Virginia.

Foresters and landowners who are responsible for deciding when trees and stands should be cut may lack the necessary economic data to make this decision. As a result, they have had to rely heavily on such natural factors as growth, vigor, and log quality to determine when to harvest.

Though both natural factors and financial maturity must be considered in conjunction with other relevant management decisions, knowledge of financial maturity greatly improves the chance of making the most profitable decisions.

Financial maturity is arrived at when the rate of value increase of the tree or stand is at, or falls below, the rate of return desired by the timber grower. This rate of value increase depends on three factors: (1) the present value of the growing stock; (2) the prospective value of the growing stock, which includes consideration of growth increase in diameter as well as in merchantable height and possible improvement in quality; and (3) the estimated time between determinations of present value and prospective value. Given these data, the rate of value increase is determined by solving for r in the compound interest formula

$$(1 + r)^n = \frac{V_n}{V_o}$$

where r is the rate of interest.
n is the time period.
V_n is the prospective value.
V_o is the present value.

We had to develop considerable basic data about lumber grade yields as well as prices to determine present value. We also had to obtain growth data to project the development of the tree over the time period used to establish prospective value.

DETERMINING PRESENT VALUE

Present value of a single tree is determined by its volume, lumber grade yield, and prices. The various units and standards that we used are described below.

Tree volume was expressed in board feet, International ¼-inch kerf rule.

Quality evaluations were based on log grades as developed by the U. S. Forest Products Laboratory for factory-lumber logs and defined in the field manual, *A guide to hardwood log grading (revised) (Ostrander and others 1965).*

Log-grade data were obtained from trees selected at random within the size classes needed. In addition to the three factory-lumber log grades (1, 2, and 3), a fourth category was recognized that included both construction and local-use-class logs. These logs, though better than cull logs, are too rough or knotty for lumber.

Lumber grade yields were obtained from the U. S. Forest Products Laboratory publication, *Hardwood lumber grades for standard lumber (Vaughan, Wollin, McDonald, and Bulgrin 1966).*

Prices were those reported in the *Hardwood market report (Lemsky 1962-66).* These prices were averaged over the 5-year period and the ratios (the price relations between these average prices for the various grades and the average price for No. 1 Common lumber) were computed (table 1).

In computing present value, the quality-index concept was used to determine the log value in terms of the amount and value of the lumber they contain.

Log-Quality Indexes and Tree-Quality Indexes

The quality-index concept (Q.I.), as developed by A. M. Herrick in 1946 and refined by other researchers since then, was used to put log grades on a lumber-value basis (*Herrick 1946*). Q.I. is a single number that expresses the relative value of a log or tree as determined by the amount of value of the different grades of 4/4 lumber (1 inch thick) that can be sawed from the log or tree (appendix I).

Thus two sets of data are essential in developing Q.I.: (1) lumber-grade yields by log grade, log diameter, and species; and (2) lumber-price relatives (price ratios with No. 1 Common as the base grade, derived from applicable regional price reports and averaged for a period of 5 years).

Using these data, we computed log-quality indexes for each species by log grade and diameter.

Next we developed tree-quality indexes based on the volume and quality index of each log in the tree (appendix II).

Developing Conversion Values

The versatility of tree-quality indexes is well illustrated in determining conversion values. Only the volume of the tree and the price of No. 1 Common lumber is needed to convert the tree-quality index to monetary terms, and the procedure is relatively simple.

As previously mentioned, tree volumes were calculated through use of the hardwood taper table and the International $\frac{1}{4}$-inch kerf rule.

Table 1.—*Lumber price relatives**

Species	Lumber grade					
	FAS	SEL	1C	2C	3A	3B
Red oak	1.74	1.65	1.00	0.67	0.59	0.40
White oak	1.90	1.81	1.00	.68	.59	.40
Chestnut oak	1.90	1.81	1.00	.68	.59	.40

*Based on 1962-1966 *Hardwood Market Report* prices for Appalachian hardwoods, f.o.b. mills in the area of Johnson City, Tennessee. 4/4 plain-sawed No. 1 Common grade was used as the reference.

The *Hardwood market report* of January 6, 1968 *(Lemsky 1968)* was used to obtain prices of 4/4 No. 1 Common lumber. Specifically, the Appalachian hardwood prices based on f.o.b. mill in the area of Johnson City, Tenn., were used. Prices were $122 per thousand for 4/4 No. 1 Common red oak and $120 per thousand for 4/4 No. 1 Common white oak and chestnut oak.

The per-thousand gross value of the lumber in trees of various diameters and merchantable heights was determined by multiplying the tree-quality index by the appropriate price per thousand.

To determine the net value per thousand of the lumber in the tree, it was necessary to deduct conversion costs. These are the costs involved in converting the standing tree into lumber. The bulk of these costs consists of labor and materials used in felling and bucking the trees, skidding and loading, other general logging costs, transportation, and milling costs involved in sawing the logs into lumber. For this study, average costs of $70 per thousand were used for 16-inch d.b.h. trees. Costs were adjusted and curved by tree diameters, and the resulting values were applied by tree d.b.h. class (table 2). We recognize that these costs may vary widely by logging chance and by sawmill.

Changes in conversion costs profoundly affect the rate of value increase because they affect the magnitude of the present conversion value that is to be carried forward into the future. In general, the lower the conversion costs, the lower the expected rate of value increase; and conversely, the higher the conversion

Table 2.—*Conversion costs for hardwood trees*

D.b.h. (inches)	Cost per thousand board feet
12	$78.85
14	74.50
16	70.00
18	65.70
20	61.35
22	57.00
24	53.50
26	52.25
28	51.95
30	51.85

costs, the higher the rate of return. These effects are somewhat dampened in the larger diameter classes. For example, the expected rates of value increase at various levels of conversion costs are:

	$60.00	*$70.00*	*$80.00*
16-inch d.b.h. — 1 log	7.3	8.1	9.6
30-inch d.b.h. — 1 log	1.5	1.6	1.6

Having determined the net value per thousand of the lumber in the tree by deducting the appropriate conversion costs, the next step was to calculate the conversion value (the present value of the tree). This was done by multiplying the net value per thousand by the appropriate tree volumes.

Thus, once tree-quality indexes are established, the calculation of present value can be summarized as follows:

1. Tree Q.I. × price for No. 1C per thousand = gross value per thousand.
2. Gross value per thousand — conversion cost = net value per thousand.
3. Net value per thousand × volume in tree = conversion value or present tree value.

DETERMINING PROSPECTIVE VALUE

Prospective value is the present value plus the increase in value due to diameter growth, the increase in merchantable height, and possible improvement in quality. In our study, prospective value was based on an assumed increase in tree value over the next 10 years. We also assumed that there would be no change in the market price of lumber. (An increase in price would result in a higher rate of value increase while a lower market price for lumber would result in a lower rate.)

D. b. h.-Growth Predictions

Tree growth within a species varies with several factors that the forest manager must recognize to apply growth to a given situation. For this reason tree growth was stratified by: (1) the ability of an area of forest land to grow trees (site quality); (2) the competitive condition of a tree in the stand (its vigor

class); and (3) the size of the tree. Ten-year growth predictions were based on results of a study made of increment-core data *(Trimble 1960)*.

Diameter growth of sawtimber-size trees varied with species, tree-vigor class (definitions in appendix III), and site (definitions in appendix IV). The data were taken in well-stocked even-aged stands. The effect of stand density variations was not measured, but it is at least partially reflected in tree-vigor class. Only for vigor-class I trees did growth vary with d.b.h.: it decreased as the trees got bigger. Although this trend was detected only for vigor I trees, we know that this trend is a natural one, and we made adjustments so that it was reflected in the growth rates of the other vigor classes also (appendix V, tables 13, 14, 15, and 16).

In applying these diameter-growth predictions to the calculation of the rate of value increase, we made only two relatively minor assumptions: (1) that vigor classes would remain the same during the next 10 years, and (2) that vigor IV trees would never be considered as leave trees. Thus we did not calculate rate of value increase for this class.

Height-Growth Predictions

During the 10-year period for which value increases are projected, trees may increase in merchantable height. To guide the projection of log height increase, we made these assumptions:

1. Trees growing 2.0 inches d.b.h. and more during the 10-year period could potentially increase a full 16-foot log in merchantable height. And trees growing less than 2.0 inches d.b.h. in 10 years were restricted to a half-log increase in merchantable height.

2. Log-height increases are related to d.b.h. A tree that has a 16-foot merchantable stem at 20 inches d.b.h. has its merchantable length limited by stem breakup into crown, and its merchantable length will not increase with d.b.h. growth. For computation purposes, we set the following log-height-increase limitations:

Present d.b.h. (inches)	*Tree height classes that will not increase in height in next 10 years*
16	1-log trees
18	1- and 1½-log trees
20	1-, 1½-, and 2-log trees
22	1-, 1½-, 2, and 2½-log trees
24	1-, 1½-, 2-, 2½-, and 3-log trees
26	No increase in log height for any tree 26 inches d.b.h. or more.

3. Maximum log height used in the computation was 56 feet.

Quality-Improvement Predictions

Quality denotes value and in the development of a tree any improvement in quality will result in an appreciable increment in the rate of value increase. These assumptions guided us in our quality-improvement predictions:

1. The maximum butt-log grade improvement in the 10-year period was assumed to be one grade class. This may have been a conservative estimate for the better sites.
2. For red oak and chestnut oak, there was little prospect of grade improvement for butt-log grade 3 stems above 22 inches d.b.h. So we computed no grade improvement in these species above 22 inches; value increase was based only on d.b.h. and log-height increase. For white oak there was practically no improvement in butt-log grade 3 stems over 27 inches d.b.h.; so we computed no grade improvement above this size for grade 3 trees *(Trimble 1965)*.
3. In trees larger than 15 inches d.b.h. we computed no improvement in butt-log grade for trees with butt logs of construction or local-use grades. Such trees should be marked for early cutting.

Developing Prospective Value

Diameter growth, height growth, and quality improvement were considered to be important factors affecting the value increase of the tree over the 10-year period.

Diameter growth is given in the growth tables by site class and tree size. Future merchantable height and future log quality must be estimated by the observer, and guides for this purpose have

been described. Through the use of the growth data and the assumptions on height and log quality changes, we can project the development of a tree and estimate its diameter, grade, merchantable height, and stumpage value at the end of the 10-year period. Several combinations of these factors are possible, such as: no increase in grade or log height, or an increase in grade or log height, or an increase in grade but not log height. Several other combinations are possible, limited only by our assumptions about these factors (table 3).

Assume that we have growing on a site index of 80 x 16-inch d.b.h., vigor I red oak tree with a butt-log grade of 2, and 24 feet of merchantable height. From table 13 in the appendix we can find a predicted growth rate for the 10-year period of 2.7 inches. Thus the predicted future d.b.h. of this red oak is 18.7 inches.

With regard to log grade, we find in our quality-improvement assumptions that this tree can improve one log grade in the 10-year period — the future tree can have a butt-log grade of 1 or 2. And with regard to height growth, we assumed an increase of a full 16-foot log; therefore we have three possible merchantable heights — 24, 32, and 40 feet. Thus six combinations of these factors exist:

Diameter (inches)	*Butt-log grade*	*Merchantable height (feet)*
18.7	2	24
	2	32
	2	40
	1	24
	1	32
	1	40

Conversion value (the prospective values for these possible combinations) is calculated in the same manner as the present value.

DETERMINING THE RATE OF VALUE INCREASE

Computation of the rate of value increase is based on the relationship between the present value and the prospective value 10 years hence, as depicted in the compound interest formula:

$$(1 + r)^n = \frac{V_n}{V_o}$$

Table 3.—*Determination of rate of value increase for 16-inch d.b.h. red oak, vigor I, site index 80**

Present				Future				Ratio V_n/V_o	Rate of value increase (percent)	Ten-year value increase (dollars)
D.b.h. (inches)	Butt-log grade	Log height (feet)	Tree value (dollars)	D.b.h. (inches)	Butt-log grade	Log height (feet)	Tree value (dollars)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
16	1	16	3.01	18.7	1	16	6.57	2.183	8.1	3.56
16	2	16	.90	18.7	2	16	2.83	3.144	12.1	1.93
16	2	16	.90	18.7	1	16	6.57	7.300	22.0	5.67
16	1	24	3.75	18.7	1	24	8.52	2.272	8.6	4.77
16	1	24	3.75	18.7	1	32	9.46	2.523	9.7	5.71
16	1	24	3.75	18.7	1	40	9.75	2.600	10.0	6.00
16	2	24	.96	18.7	2	24	3.55	3.698	14.0	2.59
16	2	24	.96	18.7	2	32	3.77	3.927	14.7	2.81
16	2	24	.96	18.7	2	40	3.66	3.813	14.3	2.70
16	2	24	.96	18.7	1	24	8.52	8.875	24.4	7.56
16	2	24	.96	18.7	1	32	9.46	9.854	25.7	8.50
16	2	24	.96	18.7	1	40	9.75	10.156	26.1	8.79
16	1	32	4.05	18.7	1	32	9.46	2.336	8.9	5.41
16	1	32	4.05	18.7	1	40	9.75	2.407	9.2	5.70
16	1	32	4.05	18.7	1	48	9.73	2.402	9.2	5.68
16	2	32	.77	18.7	2	32	3.77	4.896	17.2	3.00
16	2	32	.77	18.7	2	40	3.66	4.753	16.9	2.89
16	2	32	.77	18.7	2	48	3.34	4.338	15.8	2.57
16	2	32	.77	18.7	1	32	9.46	12.286	28.5	8.69
16	2	32	.77	18.7	1	40	9.75	12.662	28.9	8.98
16	2	32	.77	18.7	1	48	9.73	12.636	28.9	8.96
16	1	40	3.77	18.7	1	40	9.75	2.586	10.0	5.98
16	1	40	3.77	18.7	1	48	9.73	2.581	9.9	5.96
16	2	40	.35	18.7	2	40	3.66	10.457	26.4	3.31
16	2	40	.35	18.7	2	48	3.34	9.543	25.3	2.99
16	2	40	.35	18.7	1	40	9.75	27.857	39.5	9.40
16	2	40	.35	18.7	1	48	9.73	27.800	39.4	9.38

*No computations are shown for trees with negative present or future stumpage values as in the case of trees with a butt-log grade of 3 or local-use and construction grade.

To continue our example of the 16-inch d.b.h. red oak used in the previous section, we can now calculate the rate of value increase. Given the units of present conversion value (table 3, column 4) and prospective conversion value (column 8), it is a relatively easy matter to determine the values for V_n/V_o (column 9) for the six possible future combinations of this 16-inch red oak 10 years in the future. Given these values for V_n/V_o, the rate of value increase (r) is determined by looking up the rates for these values in the compound-interest tables for $(1 + r)^{10}$ (column 10). Thus the rate of value increase for a 16-inch d.b.h., vigor-1 red oak tree with a butt-log grade of 2 and with 24 feet of merchantable height, growing on site index 80, can vary from 14.0 percent to 26.1 percent, depending on the changes in merchantable height and quality.

On the basis of diameter growth alone, this red oak can achieve an estimated 14.0 percent rate of value increase. Diameter growth plus an increase of 1 log merchantable height will result in an estimated 14.3-percent rate of value increase. However, the greatest gains in the rate are achieved when quality is increased one grade. Here the estimated rates are advanced 24.4 to 26.1 percent depending upon what additional height growth is made. This example illustrates the importance of quality improvement.

Throughout the development of the rate of value increase it was apparent that the resulting final tables would not depict the situation for all users of these tables and that the rate for any specific tree was but an estimation. In producing the quality indexes, a major factor in variation is the assumption of lumber-grade recovery of 4/4 factory-grade lumber. Few, if any, mills would duplicate exactly this recovery. They may increase or decrease the value of products recovered through producing different thicknesses or products. The use of a specific set of conversion costs (table 2) is another necessary generalization that may or may not fit the existing situation for a timber stand or logging crew.

For these and other reasons a presentation of specific rates of value increases would be illusionary and could possibly lead to

improper usage. Instead, we decided ranges of rates were more useful. Thus tables 4 to 6 show the rate of value increase as a range of rates for a site index and a vigor class. Once the site index is determined for a stand, the cruiser need only find the diameter and vigor of the tree to determine the range of rate of value increase due to growth only that can be expected in the next 10 years. If the cruiser estimates that the tree will improve in quality to a higher butt-log grade class during this period he can look for a value increase rate in tables 4 to 6 under the section "Due to growth and quality increase."

INTERPRETING THE RATE-OF-VALUE-INCREASE CONCEPT

The rate of value increase is supplemental to the silvicultural and management considerations that must be made to ensure the proper development of present and future crops of timber. However, the rate-of-value-increase concept does reveal certain generalities about the financial development of a tree. These are:

Tree earning power decreases with increasing tree size.—A 14-inch d.b.h. vigor-1 red oak on site index 80 potentially can earn up to 30 percent annually over the next 10 years, based on growth alone, and up to 46 percent based on growth and possible quality (log grade) improvement. On the other hand, a 26-inch tree on the same site quality and of the same vigor class will earn about 2½ percent in growth alone and a maximum of 9 percent if a grade improvement occurs—an unlikely event in so large a tree.

Earning power is greatly increased by improvement in log grade.—As trees develop, many of them may be expected to improve in quality. Tables 4 to 6 illustrate the important gains to be made through quality improvement. For example, an 18-inch vigor-I red oak tree on an excellent site may increase in value up to 22 percent annually if a log-grade improvement takes place in the next 10 years (table 4). On the other hand, the rate of value increase due to growth alone would not exceed 12 percent over the same interval. Many small trees with grade-3 butt logs

Table 4.—*Expected rate of value increase for red oak trees, in percent*[1]

D.b.h. (inches)	Due to growth only				Due to growth and quality increase[2, 3]			
	Vigor I		Vigor III		Vigor I		Vigor III	
	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50
14	28-30	21	13-15	12-14	42-46	37-40	34-37	34-36
16	8-27	5-20	4-15	3-14	22-40	19-35	17-33	16-32
18	6-12	4- 8	3- 6	2- 5	16-22	14-19	12-17	12-16
20	5- 9	3- 5	2- 4	1- 3	13-17	11-14	10-13	10-12
22	4- 6	2- 3	2- 3	1- 2	11-45	9-43	9-42	8-41
24	3- 4	—	1- 2	—	9-10	—	8	—
26	2- 3	—	1	—	9	—	7- 8	—
28	2	—	0- 1	—	8- 9	—	7	—
30	2	—	—	—	8	—	7	—

[1] Based on 4/4 factory-grade lumber recovery. These rates can have a variation of 2 to 4 percent due to differences in location, volume estimates, and quality estimates.

[2] The high portion of the range in rates is due largely to low-grade trees that have a low present value and thus produce a relatively high rate of value increase when considered in the ratio V_n/V_o. For this reason, butt-log grade 3 logs have not been considered in the estimates "due to growth only."

[3] The high rates of value increase in the 22-inch diameter class are due to the improvement of butt-log grade 3 trees to butt-log grade 2.

Table 5.—*Expected rate of value increase for white oak trees, in percent*[1]

D.b.h. (inches)	Due to growth only				Due to growth and quality increase[2, 3]			
	Vigor I		Vigor III		Vigor I		Vigor III	
	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50
14	5-13	4- 8	4- 8	2- 6	17-26	15-21	15-21	14-19
16	5-10	2- 6	2- 6	0- 4	16-38	13-35	13-35	11-34
18	3- 7	1- 4	2- 4	0- 3	14-31	11-28	12-28	10-27
20	3- 6	0- 3	0- 3	0- 2	9-15	7-12	7-13	6-11
22	2- 4	0- 2	0- 2	0- 1	5-13	3-11	3-11	2-10
24	2- 3	—	1- 2	—	3-12	—	2-11	—
26	1- 2	—	1	—	1-12	—	0-11	—
28	1- 2	—	0- 1	—	11-12	—	11	—
30	1- 2	—	0- 1	—	12	—	11-12	—

[1] Based on 4/4 factory-grade lumber recovery. These rates can have a variation of 2 to 4 percent due to differences in location, volume estimates, and quality estimates.

[2] The high portion of the range in rates is due largely to low-grade trees that have a low present value and thus produce a relatively high rate of value increase when considered in the ratio V_n/V_m. For this reason butt-log grade 3 logs have not been considered in the estimates "due to growth only."

[3] The high rates of value increase in the 16- and 18-inch diameter classes are due to the improvement of butt-log grade 3 trees to butt-log grade 2.

Table 6.—*Expected rate of value increase for chesnut oak trees, in percent*[1]

D.b.h. (inches)	Due to growth only				Due to growth and quality increase[2]			
	Vigor I		Vigor III		Vigor I		Vigor III	
	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50	S.I. 80	S.I. 50
14	18-25	11-16	9-14	7-11	34-43	30-39	30-39	29-37
16	5-14	3- 8	2- 7	2- 5	21-25	19-22	18-21	17-21
18	3- 9	2- 4	2- 4	1- 3	15-27	14-23	13-22	12-21
20	3- 6	1- 3	1- 3	0- 2	11-15	8-12	8-12	7-11
22	3- 5	1- 2	1- 2	0- 1	8-11	6- 9	6- 9	5- 8
24	2- 3	—	1	—	6- 8	—	5- 7	—
26	2- 2	—	1	—	5- 7	—	4- 6	—
28	1- 2	—	0- 1	—	4- 7	—	4- 6	—
30	1- 2	—	0- 1	—	4- 6	—	3- 5	—

[1] Based on 4/4 factory-grade lumber recovery. These rates can have a variation of 2 to 4 percent due to differences in location, volume estimates, and quality estimates.

[2] The high portion of the range in rates is due largely to low-grade trees that have a low present value and thus produce a relatively high rate of value increase when considered in the ratio V_n/V_o. For this reason butt-log grade 3 logs have not been considered in the estimates "due to growth only."

have low or negative conversion values. When such trees are vigorous and are low grade only because they are small, they may be retained in the stand; but if they do not have the potential for grade improvement they should be removed as soon as possible. Though low-grade vigorous trees may earn a high interest rate, the actual monetary gain would be small and the stand earning power for a forest would be low when land-investment values are considered.

We emphasize that the probability of grade improvement decreases with increasing tree size. In stands in which thinnings or improvement cuttings have been made, the likelihood of future grade improvement for 22-inch trees would be slight indeed because the best quality stems would have been favored in previous markings *(Trimble 1965)*. In unmanaged stands the potential of log-grade improvement in the oaks is very low after trees reach 24 inches d.b.h.; and in deciding which trees of such diameters to leave, reliance should be placed almost solely on rate of return based on volume growth alone. In managed stands the critical d.b.h. is lower—perhaps about 20 inches—and would vary somewhat with the intensity of previous management.

Trees with greater merchantable height have, on the average, slightly higher earning rate potential if vigor class, butt-log grade, and site quality are the same.—This does not mean that a log-height increase in the near future increases tree earning power: it actually means that of two trees whose merchantable height is limited by the location of the crown, the one with the longer merchantable bole will increase more in value over a given period, other considerations being equal. The effect of log-height increase in a tree may increase the earning rate or it may decrease it. If the volume added in height growth has a positive conversion value, percent return is increased; if it has a negative value—as in the case of small grade-3 logs—it is decreased. In general, log-height increases will be limited to the smaller trees — less than 18 inches d.b.h. — and the volume added will decrease tree earning power over the 10-year period even though it may have potential for increasing it over a longer period.

Marking Guides

Marking guides, based on tree earning power and to some extent on generally recognized marking principles, include: (1) guides for selection cutting under all-aged systems, for improvement cutting in previously unmanaged stands, and for sawlog thinnings in stands managed under an even-aged system; and (2) guides to setting average tree diameters for harvest cuttings (rotation tree size) under even-aged management.

For this latter use these guides can only be assumed appropriate for stands now at, or nearing, financial maturity. Extending the use of these evaluations beyond 10 to 15 years into the future is risky because probable changes in marketing and utilization practices may completely alter rates of return.

Because most oak stands that will be cut in the near future are some combinations of immature, previously unmanaged, or very lightly managed stands, the guides will be most useful in marking for partial cutting. And they probably will be useful in guiding improvement cuttings and thinnings in immature stands that will eventually be clearcut under some even-aged system. Used in such a way they must be considered in conjunction with residual stocking guides.

Partial Cutting

In all three species on all sites the trees to be discriminated against are: (1) culls and near culls, (2) trees with butt logs of local-use grade, (3) trees of any size in vigor-class IV, and (4) trees over 15 inches d.b.h. with butt logs of construction grade. Again, for all three species on all sites the trees to be favored and left are: (1) those with an imminent improvement in butt-log grade; (2) vigor-class I trees over vigor II and III, and vigor II over vigor III; (3) trees of greater merchantable length over trees of less merchantable length, other factors being similar; and (4) smaller diameter sawlog trees over larger sawlog trees with similar grade and vigor classes.

Rotation Size

After proper consideration of silvicultural and management needs, the rate-of-value-increase concept can also be utilized to

determine rotation size in even-aged stands. These guides, presented separately by species in tabular form (tables 7, 8, and 9) are given for three interest-rate objectives—2, 4, and 6 percent. The diameters given are average stand diameters. In choosing a 2-percent interest rate objective, as in a case where multiple use applies, the first two columns of diameters would be used to determine the financial maturity. For example, given an area of site index 50, where trees would average about 1 log merchantable height, the top d.b.h. limit to leave for a 2-percent return on vigor-I red oak trees would be 23 inches (table 7). Trees grown larger than 23 inches would fail to provide a return of 2 percent. In this same example, where a 4-percent return is required, the top d.b.h. would be 19 inches; and for a 6-percent return the d.b.h. limit would be 17 inches.

Although the data are presented as guides for harvest cuttings under even-aged management, they can also serve as guides to partial cutting where no grade improvement is in prospect for the tree in question. We emphasize that the diameters in these tabular guidelines are based on value increases due to growth rate alone; therefore, they should be adjusted upward where potential log grade increase is involved.

The tabular data reflect earning power of trees with butt-log grades of 1 and 2. If trees with butt-log grades of 3 had been included, the smaller trees would have shown higher rates of return, which would have increased the financial maturity diameters. However, as previously stated, these butt-log grade 3 trees earn little money even though rates of return are high. Certainly above 15 inches in diameter they would be discriminated against in marking. The blanks in the tables mean that the rate of interest cannot be obtained with any size sawtimber trees of butt-log grades 1 and 2. If marking is made in areas of tree populations that fall largely under the category of low vigor, poor site, and small diameter, then the general guides given above under "partial cutting" should govern, and specific d.b.h. limitations are unimportant.

As a word of caution in interpreting tables 7, 8, and 9, users should remember that the interest rates are based on trees already

existing in a stand and on their projected value increase over the next 10 years. Costs of growing the stand to sawtimber size were not considered. To illustrate this point, we doubt that oaks can be grown at cost to small sawlog size on site-index-50 land — even though in a stand already grown to small sawlog size, a number of individual stems will earn a low rate of interest over the next 10 years.

Table 7.—*Red oak diameters for financial maturity, in inches, based on value increase determined by growth rate alone*
(Based on trees with butt-log grades of 1 and 2)

Site index	Average log height	Percent return and vigor class					
		2		4		6	
		I	II	I	II	I	II
80	2½	28	25	22	21	20	18
70	2	26	24	22	20	19	17
60	1½	24	23	20	19	18	16
50	1	23	22	19	18	17	16

Table 8.—*White oak diameters for financial maturity, in inches, based on value increase determined by growth rate alone*
(Based on trees with butt-log grades of 1 and 2)

Site index	Average log height	Percent return and vigor class					
		2		4		6	
		I	II	I	II	I	II
80	2½	25	23	20	18	17	15
70	2	23	22	18	17	16	14
60	1½	21	20	17	16	15	—
50	1	19	18	16	15	14	—

Table 9.—*Chestnut oak diameters for financial maturity, in inches, based on value increase determined by growth rate alone*
(Based on trees with butt-log grades of 1 and 2)

Site index	Average log height	Percent return and vigor class					
		2		4		6	
		I	II	I	II	I	II
80	2½	26	23	20	19	17	16
70	2	24	22	19	18	17	16
60	1½	23	21	18	17	16	15
50	1	20	19	17	16	15	15

LITERATURE CITED

Herrick, Allyn M.
1946. GRADE YIELDS AND OVERRUN FROM INDIANA HARDWOOD SAWLOGS. Purdue Univ. Agr. Exp. Sta. Bull. 516, 60 pp., illus.

Herrick, Allyn M.
1956. THE QUALITY INDEX IN HARDWOOD SAWTIMBER MANAGEMENT. Purdue Univ. Agr. Exp. Sta. Bull. 632, 26 pp., illus.

Land, G.
1962-66. HARDWOOD MARKET REPORT. Memphis, Tennessee.

Lemsky, Abe.
1968. HARDWOOD MARKET REPORT. Memphis, Tennessee.

Ostrander, M. D., and others.
1965. A GUIDE TO HARDWOOD LOG GRADING (REVISED). U.S.D.A. Forest Serv. NE. Forest Exp. Sta., 50 pp., illus.

Schnur, Luther G.
1937. YIELD, STAND, AND VOLUME TABLES FOR EVEN-AGED UPLAND OAKS. U. S. Dep. Agr. Tech. Bull. 560, 87 pp., illus.

Trimble, G. R., Jr.
1965. IMPROVEMENT IN BUTT-LOG GRADE WITH INCREASE IN TREE SIZE, FOR SIX HARDWOOD SPECIES. U. S. Forest Serv. Res. Paper NE-31, 15 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Trimble, George R., Jr.
1960. RELATIVE DIAMETER GROWTH RATES OF FIVE UPLAND OAKS IN WEST VIRGINIA. J. Forestry 58: 111-115.

Vaughan, C. L., A. C. Wollin, K. A. McDonald, and E. H. Bulgrin.
1966. HARDWOOD LUMBER GRADES FOR STANDARD LUMBER. U. S. Forest Serv. Res. Paper FPL-63, 52 pp., illus. Forest Prod. Lab., Madison, Wisc.

■

Log-Quality Index

In equation form Q.I. appears as:

$$\text{Q.I.} = (\%\ \text{FAS} \times \text{P.R.}_{\text{FAS}}) + (\%\ \text{SEL} \times \text{P.R.}_{\text{SEL}}) + (\%\ _{\#1\text{C}} \times \text{P.R.}_{\#1\text{C}}) \ldots + (\%\ _{\#3\text{A}} \times \text{P.R.}_{\#3\text{A}})$$

in which —

% FAS means the percentage of the total volume of the lumber that could be sawed from the log or tree that would grade first and seconds.

P.R._{FAS} means the standard price relative for FAS lumber *(Herrick 1956)*.

Tree-Quality Index

Tree quality index = (% of tree volume in 1st log × log $\text{Q.I.}_{\text{1st log}}$) + (% of tree volume in 2nd log × log $\text{Q.I.}_{\text{2nd log}}$) + (% of tree volume in nth log × log $\text{Q.I.}_{\text{n log}}$).

The percent of tree volume in each log is determined by means of a hardwood taper table, which provides the diameter inside bark at the small end of each log; and the International 1/4-inch kerf volume table, which provides the volume of each log as well as the volume of the total merchantable height of the tree.

After tree-quality indexes were developed for each sample tree, regression analyses were used to develop tree Q.I. for each species by butt-log grade (for log grades 1, 2, and 3), diameter and merchantable height (tables 10, 11, and 12). Our examination of the log-grade data for trees with butt-log grades below 3 showed that in most cases such trees had a total tree grade below 3—regardless of species, diameter, or log height. Therefore, a tree Q.I. of 0.400 was assigned to all such trees (0.400 is a nominal value corresponding to the price relative for lumber grade 3B).

Table 10.—*Tree-quality index for red oak*

D.b.h. (inches)	Merchantable height in feet to an 8-inch diameter inside bark (d.i.b.) top					
	16	24	32	40	48	56
	BUTT-LOG GRADE 1					
16.0	0.834	0.795	0.757	0.718	—	—
18.0	.887	.848	.809	.770	0.731	—
20.0	.939	.900	.862	.823	.784	0.745
22.0	.992	.953	.914	.875	.837	.798
24.0	1.044	1.005	.967	.928	.889	.850
26.0	1.097	1.058	1.019	.980	.942	.903
28.0	1.149	1.110	1.072	1.033	.994	.955
30.0	1.202	1.163	1.124	1.085	1.047	1.008
	BUTT-LOG GRADE 2					
14.0	0.625	0.603	0.582	—	—	—
16.0	.652	.631	.609	0.587	—	—
18.0	.680	.658	.637	.615	0.593	—
20.0	.707	.686	.664	.642	.621	0.599
22.0	.735	.713	.692	.670	.648	.627
24.0	.762	.741	.719	.697	.676	.654
26.0	.790	.768	.746	.725	.703	.682
28.0	.817	.796	.774	.752	.731	.709
30.0	.845	.823	.801	.780	.758	.737
	BUTT-LOG GRADE 3					
12.0	0.440	0.431	—	—	—	—
14.0	.447	.438	0.430	—	—	—
16.0	.455	.446	.437	0.428	—	—
18.0	.462	.453	.445	.436	0.427	—
20.0	.470	.461	.452	.443	.434	0.425
22.0	.477	.468	.459	.451	.442	.433
24.0	.484	.476	.467	.458	.449	.440
26.0	.492	.483	.474	.465	.457	.448
28.0	.499	.491	.482	.473	.464	.455
30.0	.507	.498	.489	.480	.472	.463

Table 11.—*Tree-quality index for white oak*

D.b.h. (inches)	Merchantable height in feet to an 8-inch diameter inside bark (d.i.b.) top					
	16	24	32	40	48	56
	BUTT-LOG GRADE 1					
16.0	0.970	0.889	0.809	0.729	—	—
18.0	1.041	.961	.881	.800	0.720	—
20.0	1.113	1.033	.952	.872	.792	0.712
22.0	1.185	1.105	1.024	.944	.864	.783
24.0	1.257	1.176	1.096	1.016	.935	.855
26.0	1.328	1.248	1.168	1.087	1.007	.927
28.0	1.400	1.320	1.239	1.159	1.079	.998
30.0	1.472	1.391	1.311	1.231	1.150	1.070
	BUTT-LOG GRADE 2					
14.0	0.717	0.685	0.653	—	—	—
16.0	.730	.698	.666	0.634	—	—
18.0	.743	.711	.679	.647	0.615	—
20.0	.756	.724	.692	.660	.628	0.596
22.0	.769	.737	.705	.673	.641	.609
24.0	.782	.750	.718	.686	.654	.622
26.0	.795	.763	.731	.699	.667	.635
28.0	.808	.776	.744	.712	.680	.648
30.0	.821	.789	.757	.725	.693	.661
	BUTT-LOG GRADE 3					
12.0	0.526	0.503	—	—	—	—
14.0	.560	.537	0.514	—	—	—
16.0	.594	.571	.548	0.525	—	—
18.0	.628	.605	.582	.559	0.536	—
20.0	.662	.639	.616	.594	.571	0.548
22.0	.696	.673	.651	.628	.605	.582
24.0	.731	.708	.685	.662	.639	.616
26.0	.765	.742	.719	.696	.673	.650
28.0	.799	.776	.753	.730	.707	.684
30.0	.833	.810	.787	.764	.741	.719

Table 12.—*Tree-quality index for chestnut oak*

D.b.h. (inches)	Merchantable height in feet to an 8-inch diameter inside bark (d.i.b.) top					
	16	24	32	40	48	56
			BUTT-LOG GRADE 1			
16.0	0.930	0.888	0.846	0.804	—	—
18.0	.940	.898	.856	.814	0.773	—
20.0	.950	.909	.867	.825	.783	0.741
22.0	.961	.919	.877	.835	.793	.752
24.0	.971	.928	.888	.846	.804	.762
26.0	.982	.940	.898	.856	.814	.773
28.0	.992	.950	.908	.867	.825	.783
30.0	1.003	.961	.919	.877	.835	.793
			BUTT-LOG GRADE 2			
14.0	0.649	0.636	0.621	—	—	—
16.0	.667	.653	.638	0.624	—	—
18.0	.684	.670	.655	.641	0.627	—
20.0	.701	.687	.672	.658	.644	0.630
22.0	.718	.704	.690	.675	.661	.647
24.0	.735	.721	.707	.693	.678	.664
26.0	.752	.738	.724	.710	.695	.681
28.0	.769	.756	.741	.727	.713	.698
30.0	.786	.773	.758	.744	.730	.715
			BUTT-LOG GRADE 3			
12.0	0.529	0.529	—	—	—	—
14.0	.544	.544	0.544	—	—	—
16.0	.558	.558	.558	0.558	—	—
18.0	.572	.572	.572	.572	0.572	—
20.0	.586	.586	.586	.586	.586	0.586
22.0	.600	.600	.600	.600	.600	.600
24.0	.614	.614	.614	.614	.614	.614
26.0	.628	.628	.628	.628	.628	.628
28.0	.643	.643	.643	.643	.643	.643
30.0	.657	.657	.657	.657	.657	.657

Tree-Vigor-Class-Definitions

Vigor I.—A tree in this vigor class has a large, healthy, full crown in a dominant or co-dominant position. Half or more of the crown is exposed to direct sunlight. The crown is dense, with no evidence of disease or injury. Crown quality and position are more important than total length. The bark and twigs have good color and vigorous appearance.

Vigor II.—A tree in this vigor class has a fair-sized crown in a co-dominant position. Less than half the crown is exposed to direct sunlight. The crown is less dense and not so perfect as that of a vigor I tree. This class may also include a large-crowned tree that fails to meet the requirements of vigor I because of mechanical injury or dying limbs.

Vigor III.—A tree in this vigor class has a medium to small crown usually in an intermediate position. Only the tip is exposed to direct sunlight. The crown may be open, and may have some dead or broken limbs, or may be thinly foliated. This class also includes trees with fair to large crowns in a co-dominant position that cannot meet the requirements for a vigor II tree.

Vigor IV.—A tree in this class usually has a small crown in an overtopped position. This class includes all living trees that fail to meet the requirements of higher vigor classes.

Site-Class Definitions

Site index of the oaks is the average height of dominant and co-dominant trees at 50 years of age. Site index was read for trees of measured total height and age from Schnur's curves *(Schnur 1937)*. We grouped site index by 10-foot site classes; i.e., site index 80 (75-84 feet), site index 70 (65-74 feet), site index 60 (55-64 feet), and site index 50 (45-54 feet).

APPENDIX V

10-Year D.B.H. Growth Rates

Table 13.—*10-year d.b.h. growth rates in inches for site index 80 oak*

Initial d.b.h. (inches)	Vigor-class I			Vigor-class II			Vigor-class III			Vigor-class IV		
	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak
12	3.0	2.1	2.7	2.2	1.6	2.1	1.2	1.1	1.2	0.6	0.6	0.6
14	2.8	2.0	2.5	2.1	1.5	1.9	1.1	1.1	1.1	.5	.5	.5
16	2.7	1.9	2.4	2.0	1.4	1.8	1.1	1.0	1.0	.5	.5	.5
18	2.5	1.8	2.2	1.9	1.4	1.7	1.0	1.0	.9	.5	.5	.5
20	2.4	1.7	2.1	1.8	1.3	1.6	1.0	.9	.9	.5	.5	.5
22	2.2	1.6	2.0	1.7	1.2	1.5	.9	.8	.9	.4	.4	.4
24	2.1	1.5	1.9	1.6	1.1	1.4	.9	.8	.8	.4	.4	.4
26	2.0	1.4	1.8	1.5	1.1	1.3	.8	.7	.8	.4	.4	.4
28	1.8	1.3	1.6	1.4	1.0	1.2	.7	.7	.7	.3	.3	.3
30	1.6	1.2	1.5	1.2	.9	1.1	.7	.6	.6	.3	.3	.3
32	1.5	1.1	1.4	1.1	.8	1.1	.6	.6	.6	.3	.3	.3

Table 14.—*10-year d.b.h. growth rates in inches for site index 70 oak*

Initial d.b.h. (inches)	Vigor-class I			Vigor-class II			Vigor-class III			Vigor-class IV		
	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak
12	2.7	1.8	2.3	2.0	1.4	1.8	1.2	1.0	1.1	0.6	0.6	0.6
14	2.5	1.7	2.1	1.9	1.3	1.7	1.1	1.0	1.0	.5	.5	.5
16	2.4	1.6	2.0	1.8	1.2	1.6	1.1	.9	.9	.5	.5	.5
18	2.2	1.5	1.9	1.6	1.2	1.5	1.0	.9	.9	.5	.5	.5
20	2.1	1.4	1.8	1.5	1.1	1.4	.9	.8	.8	.4	.4	.4
22	1.9	1.3	1.6	1.4	1.0	1.3	.8	.7	.8	.4	.4	.4
24	1.8	1.2	1.5	1.3	.9	1.2	.8	.7	.7	.4	.4	.4
26	1.6	1.1	1.4	1.2	.9	1.1	.7	.6	.7	.3	.3	.3
28	1.4	1.0	1.2	1.1	.8	1.0	.6	.6	.6	.3	.3	.3
30	1.3	.9	1.1	1.0	.7	.9	.6	.5	.5	.3	.3	.3
32	1.1	.7	.9	.8	.5	.7	.5	.4	.4	.2	.2	.2

Table 15.—*10-year d.b.h. growth rates in inches for site index 60 oak*

Initial d.b.h. (inches)	Vigor-class I			Vigor-class II			Vigor-class III			Vigor-class IV		
	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak
12	2.3	1.4	1.8	1.7	1.1	1.4	1.1	0.9	0.9	0.5	0.5	0.5
14	2.2	1.4	1.7	1.6	1.1	1.4	1.1	.9	.9	.5	.5	.5
16	2.0	1.3	1.6	1.5	1.0	1.3	1.0	.8	.8	.5	.5	.5
18	1.9	1.2	1.5	1.4	.9	1.2	.9	.7	.8	.4	.4	.4
20	1.7	1.1	1.4	1.3	.9	1.1	.8	.7	.7	.4	.4	.4
22	1.6	1.0	1.3	1.2	.8	1.0	.8	.6	.7	.4	.4	.4
24	1.4	.9	1.1	1.0	.7	.9	.7	.6	.6	.3	.3	.3
26	1.3	.8	1.0	.9	.6	.8	.6	.5	.5	.3	.3	.3
28	1.1	.7	.9	.8	.5	.7	.5	.4	.5	.3	.3	.3
30	1.0	.6	.8	.7	.5	.6	.5	.4	.4	.2	.2	.2

Table 16.—*10-year d.b.h. growth rates in inches for site index 50 oak*

Initial d.b.h. (inches)	Vigor-class I			Vigor-class II			Vigor-class III			Vigor-class IV		
	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak	Red oak	White oak	Chestnut oak
12	2.0	1.2	1.5	1.4	1.0	1.2	1.1	0.8	0.9	0.5	0.5	0.5
14	1.8	1.1	1.3	1.3	.9	1.1	1.0	.8	.8	.5	.5	.5
16	1.7	1.0	1.2	1.2	.8	1.0	.9	.7	.7	.4	.4	.4
18	1.5	.9	1.1	1.1	.7	.9	.8	.6	.6	.4	.4	.4
20	1.4	.8	1.0	1.0	.7	.8	.8	.6	.6	.4	.4	.4
22	1.2	.7	.9	.9	.6	.7	.7	.5	.5	.3	.3	.3
24	1.1	.6	.8	.8	.5	.7	.6	.4	.5	.3	.3	.3
26	.9	.5	.7	.6	.4	.6	.5	.4	.4	.2	.2	.3

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A Silvicultural Guide for PAPER BIRCH in the Northeast

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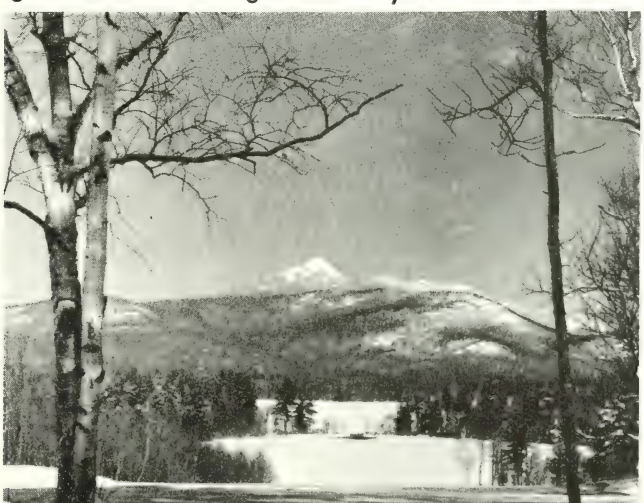
Purpose and Scope

THE PURPOSE of this paper is to provide a practical guide to the management of paper birch stands for timber production. Both the establishment of new stands and the culture of existing stands are covered. Background information on paper birch silvics, silviculture, and management is followed with a set of prescriptions describing specific treatments to be applied for a range of stand conditions and management objectives. A limited amount of information is also provided on the management of paper birch stands for aesthetic and other purposes (fig 1).

This guide is applicable only to pure paper birch stands—those in which at least 50 percent of the basal area is paper birch or those immature stands that can be modified through cleanings and thinnings to produce a stand containing at least 50 percent of the basal area in paper birch at maturity. This guide may also be used in mature stands containing less than 50 percent paper birch where the management objective calls for regeneration to paper birch. Separate guides for management of northern hardwood or spruce-fir stands containing paper birch in lesser proportions are now being prepared.

Recommendations given in this guide may be applied throughout the commercial range of paper birch in Maine, New Hampshire, Vermont, Massachusetts, and New York.

Figure 1.—Paper birch trees are one of the major ingredients of New England scenery.



A Valuable Tree

Paper birch is one of the most valuable timber trees in New England and New York. Its white sapwood, straight grain, smooth texture, and the ease with which it can be machined have made it the long-time favorite of the turning industry. As a result, it is turned, veneered, and stamped into a thousand and one useful products.

Although yellow birch is generally considered the prime timber tree in New England and New York because of the premium prices paid for veneer-quality logs (up to $350 per thousand board feet at the mill in 1968), the larger logs of paper birch also command high prices. Furthermore, woods-run prices are often higher for paper birch than for any other associated species because of the high average quality and the fact that smaller sizes of paper birch are also utilized for high-value products. Paper birch boltwood brings stumpage prices of $15 to $25 per cord (equivalent to $30 to $50 per thousand board feet) in 1968.

Paper birch is also faster growing than its valuable associates, so that it may be possible to produce two crops of paper birch

Figure 2. — Some roadside groves of paper birch, such as this one at Shelburne, New Hampshire, are far more important for their aesthetic value than for the timber they contain. But other roadside stands can contribute to both values simultaneously.

in the time required for a single rotation of yellow birch or sugar maple. The relatively short rotation possible with paper birch makes investments in intensive culture, such as early thinnings, economically feasible. Because of its fast growth and its high value in small sizes, paper birch may actually be cultured more profitably than any other hardwood in the region.

Paper birch is also a valuable tree aesthetically. Its showy bark makes it a distinctive feature of the northern landscape. Roadside groves of paper birch are important tourist attractions in a region where recreation is a major industry (fig 2).

OCCURRENCE IN THE NORTHEAST

Paper birch is one of the principal components of three forest types as recognized by the Society of American Foresters: the paper birch type, the paper birch-red spruce-balsam fir type, and the white spruce-balsam fir-paper birch type. In addition, it is an associate species in 13 softwood types and 4 hardwood types. The area in softwood and hardwood types is about equal. These forest types containing paper birch cover about 81 percent of the commercial forest land in the region. Pure paper birch stands probably cover no more than 2 or 3 percent of this area.

Paper birch is found most often in even-aged stands that have developed after heavy cutting or fire. Paper birch trees are also found in uneven-aged stands as scattered long-lived individuals or occasionally as small groups where cutting or some natural disturbance created a canopy opening.

In New England, paper birch occurs naturally throughout Maine, New Hampshire, Vermont, western Massachusetts, and northwestern Connecticut. In New York, this species is found principally from the Catskill region north to Canada, with a scattering throughout most of the remaining area.

The commercial range includes northern New England, the Berkshire Hills region of Massachusetts, and the Taconic Mountain region of New York.

Paper birch is a cold-climate tree. It occurs in areas where killing frosts can occur in the spring as late as the first week in June, and in the fall as early as the first week in September.

The average annual precipitation within the commercial range varies from 35 to 45 inches, with about one-half occurring as snow.

For the most part, paper birch grows at all elevations and on all aspects and slopes. However, it occurs only at the higher elevations and on the cooler north- and east-facing slopes in the southern portions of its natural range.

In general, paper birch occurs on podzol soils throughout most of its commercial range. However, some paper birch stands also occur on brown and gray-brown podzolic soils. Within these three great soils groups, numerous soil series and soil types are satisfactory for growing paper birch. These soils are mainly glacial tills and outwash derived from granites, schists, gneisses, sandstones, shales, slates, and limestones.

Paper birch occurs over a wide range of soil moisture conditions. It may be somewhat more abundant on drier sites than on wet or poorly drained soils. The best soils are characteristically acidic, relatively deep, moist, and moderately well-drained. Relatively thick organic horizons are also characteristic of the better sites.

The net volume of paper birch growing stock amounts to slightly more than 1.6 billion cubic feet (including 1.8 billion board feet of sawtimber). About 86 percent of this is in northern New England, 10 percent in New York, and the rest in southern New England.

Small diameter trees are the rule. In New Hampshire, 80 percent of the growing-stock volume is in pole-size trees; in Maine, 72 percent is in these small trees.

LIFE HISTORY

Silvics

Paper birch is a monoecious species: both male and female flowers are borne in catkins on the same tree. The male flowers are formed in late autumn or early winter. In the winter months they average about 1 inch long and are clearly visible from the ground. Their relative abundance at this time is a good guide to

the size of the seed crop the following fall—barring unforeseen catastrophies to either the male or female catkins. Before opening in the spring, the male catkins elongate to as much as 4 inches. The female catkins appear with the leaves in the spring; and they average 1 to 1¼ inches long. They ripen during the summer; and when fully ripe they are generally 1 to 2 inches long.

Paper birch trees begin bearing seed when about 15 years old, the optimum age extending from 40 to 70 years. Good seed crops occur about every other year. These crops may average about 1 or 2 million seeds per acre. Bumper seed crops are much less common, occurring only about 1 year in 10.

Seed dispersal begins as early as August and continues throughout the winter, but most dispersal occurs before the ground is snow-covered. Seed is dispersed by the wind and, being light in weight, can be carried long distances. However, most seed falls within 1 or 2 hundred feet of the parent tree.

Germination appears to be related to the size of the seed crop; germination is high for large crops and low for small crops. In bumper seed years, germination is uniformly high regardless of time of seed dispersal. In less productive seed years, germination is lowest at the start of seed dispersal and then improves. Paper birch sometimes produces parthenocarpic fruits—empty seeds resulting from pollination failure.

Paper birch seeds are very small (a paper birch seed weighs only about 1/50 as much as a white pine seed, for example) and thus are very sensitive to moisture and temperature conditions at germination. The newly germinated seedling is likewise small and sensitive to environmental conditions for the first few months. Even under favorable conditions, field germination is often less than 10 percent, and under average conditions it is less than 1 percent. Mortality during the first season may average 50 to 75 percent. Thus between 20 and 400 seeds may be needed to produce a single 1-year-old seedling.

Seedbed condition is most important to the regeneration of paper birch. Mineral soil is desirable for germination because of its favorable moisture condition. Mineral soil warms up faster

than the loose organic horizons but does not reach the very high temperatures occasionally found on the organic seedbeds. However, soil nutrients are concentrated in the organic layers, so that growth of paper birch is better on organic seedbeds. A mixed organic-mineral soil seedbed provides best conditions. Undisturbed litter or humus seedbeds are not usually satisfactory.

Light is also a critical factor. Regeneration sites fully exposed to sunlight dry out rapidly and often reach excessively high temperatures, leading to seedling damage or mortality. But, as the new seedlings develop, they need overhead light for both survival and growth throughout the rest of their lives.

Paper birch trees are intolerant—their ability to endure shade is relatively low. They are less tolerant than their common forest tree associates—principally sugar maple, beech, yellow birch, red spruce, white spruce, and balsam fir. For this reason paper birch generally disappears from a stand after one generation, leaving only the more tolerant species.

Paper birch is a short-lived, fast-growing tree. Trees of seedling origin reach maturity as early as 60 years of age, with a maximum age of about 140 years. Sprouts are shorter lived and usually mature at 50 to 60 years, with a maximum age of 70 to 90 years.

The most rapid growth in height and diameter occurs in the first 20 to 30 years. After this, the growth rate begins to fall off. Diameter growth rate can be increased by thinning, particularly if the thinnings are begun when the trees are young and their crowns are still expanding rapidly.

In pure stands, paper birch matures and decays earlier than when in mixture with other hardwoods or with conifers. In mature stands, the trees attain an average height of 70 to 80 feet and an average diameter of 10 to 12 inches. On the best sites, an occasional tree in old stands may exceed 30 inches in diameter and 90 feet in height.

In forest types where paper birch occurs in mixture with spruce and fir, it is not unusual to have a two-storied forest with paper birch as the overstory species. To a lesser extent, this situation also occurs when paper birch is mixed with the more tolerant hardwoods.

Principal Enemies

Many agents cause damage to paper birch. Their effects should be minimized through proper management.

Birch dieback reached epidemic proportions in certain parts of the paper birch commercial range in the 1940's and early 1950's. Large proportions of the birch timber were killed or damaged. Symptoms included lowered vigor, reduced growth, and a dying back of twigs and branches. The causes of birch dieback have never been completely identified, although the malady appears to be the result of complex soil and climatic factors, perhaps confounded by the activities of pathogens and insects. The dieback condition has subsided and is not presently considered an important threat to paper birch management. However, one cannot assume that the conditions initiating dieback will not someday recur.

Older residual paper birch trees have sometimes exhibited symptoms similar to dieback after a partial cutting. This post-logging decadence is presumed to be the result of changes in the environment resulting from the cutting operation. However, this decadence has invariably occurred only among trees that were at or near maturity.

There are no proven ways to avoid birch dieback and post-logging decadence. Maintenance of high vigor through periodic thinnings begun at an early age may help to avoid or reduce future damage from dieback. And avoidance of heavy partial cuts in paper birch stands over about 60 years old should reduce the incidence of post-logging decadence.

Other than birch dieback, which has the potential to cause much mortality, the agents most damaging to paper birch appear to be microorganisms that cause discolorations and decays. Branch stubs provide the major avenue of entry for the pathogens, which progressively discolor and then decay the xylem tissue. Discolorations alone sometimes reduce value. Red heart, which is not a natural heartwood formation, is one type of discoloration that is well known; it limits the value of the wood for some uses.

The column of discoloration and decay in the bole is almost

always limited to the central core of wood corresponding to the tree size at the time of wounding or branch death. This important fact provides a basis for controlling damage, for if the formation of new branch-stub infection courts can be avoided after the tree has attained a diameter of about 4 inches, the damage can often be avoided entirely, or at least it can be restricted to the central 4-inch knotty core, which is not used for veneer and is of low quality for sawtimber.

To do this, it is necessary to encourage pruning (either natural or artificial) of young trees, and then provide them with ample growing space as they reach pole size to reduce or stop natural pruning and encourage rapid healing of any branch stubs that do occur. It is also important to encourage pruning (either natural or artificial) of branches while they are small. Stubs of large branches or stubs of branches that formed an acute angle with the main stem (such as occur when the leader is lost and a lateral assumes dominance) are particularly serious infection courts for pathogens. In addition to the control measures mentioned above, attempts to grow paper birch should be restricted to appropriate sites. Red heart and other discolorations are thought to be much more serious on poor sites.

The principal fungi causing decays in paper birch include *Poria obliqua, Fomes igniarius,* and *Pholiota* spp.

Root problems are another source of damage to and reduced yield from paper birch. The root rot fungus *Armillaria mellea* (shoestring fungus) is often associated with a condition referred to as collar crack on paper birch. Such trees have reduced growth rate because of the root infection and are more liable to decay and wind breakage. Other fungi infect paper birch roots and cause similar damage. Trees with visible symptoms of root infection should be removed in thinnings. Again, maintenance of vigor, and care in selection of site, will reduce losses from this cause.

Many insects attack paper birch. Prominent among the leaf feeders and defoliators are the forest tent caterpillar, *Malacosoma disstria;* the birch skeletonizer, *Bucculatrix canadensisella;* the birch leaf miner, *Fenusa pusilla;* the birch leaf-mining sawfly,

Phyllotoma nemorata; and the birch casebearer, *Coleophora salmani.* The bronze birch borer *Agrilus anxius* attacks the boles of paper birch trees. It became well known because it was often associated with birch dieback. However, this borer usually attacks trees that have been weakened by some other agent, and it is not considered a primary damaging agent. Cambium miners such as *Agromyza pruinosa* cause a defect in birch lumber known as pith-ray flecks. This injury sometimes makes wood unsuitable for fine-grade veneers. Ambrosia beetles such as *Trypodendron betulae* are also important because their dark-stained galleries are an important defect in birch lumber. Insects such as *Apion walshii,* and the fungi that are associated with them, also cause considerable damage to paper birch seeds during some years.

Sapsuckers, deer, and other animals cause relatively minor damage to paper birch, although any of these agents may occasionally cause more serious problems in local areas.

The yellow-bellied sapsucker, *Sphyrapicus varius,* damages paper birch trees by pecking holes through the bark to get sap. These holes often result in discoloration and ring shake and severe sapsucker injury may lead to mortality in trees of all sizes.

Browsing by deer can cause considerable damage to paper birch regeneration. Sprouts are subject to severe browsing, and if this is continued, mortality follows. However, lightly browsed paper birch can rapidly grow above the reach of deer. Thus, if birch is to be regenerated, heavy deer browsing must be avoided.

Site Index

Site index curves for paper birch, based on a breast-height age of 50 years, are given in the appendix (fig. 6).

In mixed stands, it may be necessary to use measured site index for one species to predict the site index of another. Figure 7 (appendix) shows the relationship among site indices of paper birch, yellow birch, sugar maple, and white ash. For example, if the measured site index of yellow birch is 70, then the comparable site index for paper birch would be about 76.

Average site index for paper birch is about 60 to 70 feet. The potential production of a paper birch stand with a site index of

75 or better is high, while a site index of 55 represents fairly low potential.

The best sites commonly occur at the lower elevations, on the northeast aspects, on deep and moderately well-drained soils having thick organic horizons. The poorest sites often occur at the higher elevations, on southwest aspects, on shallow soils that are excessively drained and have shallow organic horizons.

Management Objectives

Management objectives will be determined primarily by the species mixture present or desired and by the type of products to be produced.

Most paper birch stands contain a mixture of other species, many smaller than the paper birch, perhaps even occupying intermediate or suppressed crown positions. It is fairly common for them to outnumber the paper birch stems, even in stands where paper birch represents well over half of the basal area. Stands containing 100 percent paper birch are virtually impossible to attain.

Paper birch stands yield a variety of products. Even intensive culture for paper birch veneer logs would normally result in the production of considerable additional volume in lower grade products. The management objective, therefore, will normally be the production of a mixture of products with a maximum dollar return. Usually this means that the mixture of products will have the highest possible proportion of veneer logs, sawlogs, and boltwood, and a minimum proportion of pulpwood. However, some owners on some lands may have quite different objectives. For example, a bolt mill may prefer to maximize boltwood production, or a campground owner may prefer to maximize the number of paper birch stems with little regard to their value as timber.

Since we must deal with a mixture of species and products, there will be a choice of management objectives. Five choices are provided in this guide.

FOR PAPER BIRCH TIMBER

For this, paper birch would be favored over all other species. Although the other species would not be removed unless they interfered with paper birch development, all treatments would be aimed at maximizing the proportion of paper birch, and its growth and yield. Rotations would be based on paper birch alone; when the final paper birch harvest cutting is made, a new stand of birch would be regenerated. Stands managed in this way should contain at least enough paper birch to meet the specifications in table 1 (appendix).

Objective 1

Maximum production of paper birch veneer logs and sawlogs. Some boltwood will also be produced. Site index should be 60 or above for this objective.

Objective 2

Maximum production of paper birch boltwood. This objective might apply in areas where short rotations are desired, where veneer and sawlog markets are absent, or on sites where paper birch will not grow to sawlog size (site index of less than 60).

FOR TIMBER OF MIXED SPECIES

For this choice, all valuable species might be treated equally. In thinnings, for example, some paper birch might be removed to favor higher quality stems of other species or to obtain a better balance of species. Rotation would be based on all species present rather than on paper birch alone. Where the associated species are primarily other valuable and long-lived species such as yellow birch, sugar maple, white ash, red spruce, and white spruce, the paper birch would be harvested about half-way through the rotation and a second harvest would later be obtained from the longer-lived species. Stands managed for mixed (long-lived) species should also have at least enough paper birch to meet the specifications in table 1.

Objective 3

Maximum production of high value products of all species. This objective is similar to objective 1 except that paper birch

would be considered to be on the same level of desirability as the associated species. The other species included here are those long-lived hardwood and softwood associates that mature considerably later than paper birch.

Objective 4

Maximum production of high-value products of all species on areas where other forest uses are incompatible with large clearcuttings or large-area strip cuttings. It is assumed that very carefully regulated cuttings that do not create large openings will be permissible. This objective might be used on commercial forest lands readily visible from tourist routes and scenic highways, in areas adjacent to recreation areas, and in roadside zones where cutting is permitted. It may also apply on small ownerships where clearcuttings of 1 acre or larger are undesirable for one reason or another.

FOR AESTHETICS AND OTHER PURPOSES

Objective 5

Maximum production and perpetuation of paper birch stems in paper birch groves and roadside scenic areas, paper birch seed-production areas, and other locations where the paper birch is desired for its appearance or other values and where timber production is secondary or is even prohibited.

A Management Program for Timber

Pure stands of paper birch can be established and maintained only under some form of even-aged management. Small proportions of paper birch can be maintained under uneven-aged management if group selection or heavy individual tree selection cuttings are employed, but stands containing 50 percent or more of paper birch cannot be achieved in this way. Therefore this guide contains no recommendations for uneven-aged management.

Even-aged management may be begun in stands of any age.

More often than not, stands being placed under even-aged management for the first time need a period of thinning, stand improvement, and conditioning before harvest cutting to reduce the number of age or size classes, to stimulate seed production, and to allow a majority of the trees in the stand to reach economic maturity. Too often immature stands are harvested in a rush to initiate even-aged management, and many pole timber and small saw-timber trees are cut at a time when they are making their greatest growth in value. The prescriptions presented later provide guides on when to harvest the existing stand and regenerate a new one.

REGENERATION

Many factors affect the establishment and early development of paper birch regeneration. Soil, aspect, slope, elevation, quantity and proximity of the seed supply, rainfall, amount of shade, seedbed conditions, amount of competition from other species, and deer browsing are all important. During the first year, when seeds are germinating and seedlings becoming established, abundant moisture and avoidance of excessively high soil temperature are critical requirements. Droughty soils and steep south-facing slopes are often adverse sites for these reasons. A limited supply of seed or an unusually dry year also create adverse conditions on otherwise satisfactory sites.

Sprouts are not affected nearly as much as seedlings by droughty conditions, so that sprout reproduction may supplement seedling regeneration on some areas. Sprouts are seldom abundant enough to be the major source of reproduction, nor are sprouts as desirable as seedlings in final quality. Nevertheless, trees that develop from paper birch stump sprouts can often be used for high-value products. Although the recommendations and prescriptions presented in this guide are based on seedling reproduction, it should be remembered that some stump sprout reproduction may be available to supplement the seedlings if needed.

In many situations, clearcutting or seed-tree cutting of the mature stand will be enough to obtain satisfactory seedling

paper birch regeneration. In other cases, special measures will be required: cutting methods that provide shade, seedbed preparation, and direct seeding or planting.

Clearcutting and Seed-Tree Cutting

Clearcuttings up to 100 acres in size, either with or without seed trees, will be used most frequently for harvesting the mature stand and regenerating a new one. Except for areas where environmental conditions are expected to be adverse (as discussed in the following section), or for years when seed crops are expected to be poor, or for stands that do not contain paper birch seed-producing trees, clearcutting or seed-tree cutting alone should provide adequate regeneration.

Whether or not seed trees need to be retained will depend on the size of the opening and the season of the year in which cutting is done. If the opening is relatively small—a maximum width of about 300 feet—enough seed will usually be dispersed from bordering trees so that seed trees are not needed in the clearcut area. Where the clearcutting is wider than 300 feet, seed trees may still not be needed in the clearcut area if cutting is done between late fall and early spring. Seed dispersed in the fall from trees on the area to be cut will provide for regeneration the next spring. However, if cutting is done during the summer months—after the seed from the previous fall has lost viability and before the new crop is ripened—there will be little seed in the humus to establish a new stand. (Paper birch seeds do not usually remain dormant and viable in the humus more than 1 year).

Therefore seed trees should be retained in any large clearcuttings made in June, July, August, or September. About four well-distributed paper birch seed trees should be retained on each acre to insure an adequate seed supply during normal seed years. As few as two seed trees per acre may suffice during a bumper year, but such seed crops occur infrequently.

Summer clearcutting with seed trees is recommended for most situations, because summer cuttings are desirable for reasons other than seed supply (seedbed scarification is slightly more

widespread after summer logging and additional scarification is more easily obtained). This recommendation is based on the requirement that enough paper birch seedlings be established to develop a stand of at least 50 percent paper birch. Large summer clearcuttings without seed trees would provide some paper birch regeneration, but usually not enough to permit management as a paper birch stand.

The above recommendation for summer clearcutting with seed trees is based on the assumption of an average seed crop. If the seed crop is expected to be below average (based on counts of male catkins), the cutting should either be postponed a year or special regeneration methods such as strip cutting and direct seeding should be considered.

After clearcutting of the merchantable trees, all remaining stems over 1.5 inches d.b.h. (except seed trees) should be cut or killed by girdling or with an herbicide. Stumps of vigorously sprouting species such as red maple should be drenched with a basal spray of 2, 4, 5-T ester in oil (or other effective herbicides). Basal spraying of stumps and removal of unmerchantable stems is often done at the same time, the year after cutting. The seed trees may be removed about 2 years after the cutting.

Loggers should be encouraged to scarify as much of the soil surface as possible during the felling and skidding operations. The use of heavy tractor skidders usually provides more scarified area than horses or lighter equipment. Exposure of mineral soil in this way will increase the proportion of birch in the new stand. However, removal of the humus layer should be avoided because this layer provides most of the nutrients required for adequate growth and development. A mixing of humus and mineral soil is most desirable. Logging during the winter when the ground is frozen or snow-covered will result in very little scarification.

Care must be taken in any cutting to avoid soil erosion. Logging roads and scarified areas especially need care. Waterbars and seeding of skidroads should be employed where the slope is 10 percent or more. Logging roads and skid trails should be kept as nearly on the contour as possible and should be kept away from streams and other watercourses. Necessary stream

crossings should be at right angles to the stream and should be protected by culverts where possible.

Special Methods for Difficult Areas

Clearcutting or seed-tree cutting alone will not always result in enough birch regeneration to develop paper birch stands. Special measures may be needed if the stand to be harvested is located on a south-, southwest-, or west-facing slope in excess of 10 percent, or if it is on a somewhat excessively drained soil, or if a poor seed crop is expected, or if there are fewer than four well-distributed paper birch seed-bearing trees per acre. If site index is less than 55, or if the soil is excessively drained, paper birch will probably not grow well on the site even if established there; other species should be considered for these areas.

There are three measures that can be taken to increase birch regeneration on areas with the above characteristics: the use of harvest cuttings that provide shade, the scarification of seedbeds, and the use of direct seeding or planting. These three measures may be used singly or in combination, depending upon the severity of the conditions.

Cutting methods that provide shade.—The use of cuttings that provide at least partial shade will provide higher surface soil-moisture conditions and lower surface soil temperatures and thus will increase birch seed germination and seedling survival. Where there are only moderately adverse conditions, or where investments in scarification or seeding do not seem desirable, the use of shade-type cuttings are recommended. Shade-type cuttings should be used rather than clearcutting or seed-tree cutting if a poor seed crop is expected.

The best shade cuttings are narrow strips (50 feet wide) oriented in an east-west direction, with 100-foot-wide uncut strips between them (fig. 3). After an establishment period of 2 years, a second series of 50-foot strips are cut on the south side of the original ones. The remaining strips are then cut after a second establishment period of 2 years. As in large clearcuttings, all unmerchantable stems are removed, vigorous sprouting is

Figure 3.—Clearcutting in narrow strips. The open shade cast by trees bordering these strips provides excellent conditions for paper birch regeneration.

controlled, and scarification is encouraged during logging, with appropriate measures to avoid erosion.

Small patches (less than 1 acre) may also be used like strips (fig. 4). They provide essentially the same conditions, except that new patches are much more difficult to fit in among older ones and to systematically cover the entire area in a particular stand. Such cuttings are most useful when used in combination with selection cutting under uneven-aged management and when no attempt is made to systematically cover the entire area with patches. Although their use is limited in even-aged management, patches may be employed in special circumstances on very small tracts, roadside areas, parks, or other areas where there is insufficient space for strips or where the geometric appearance of clearcut strips would be undesirable.

Shelterwood cuttings might also be used where strips are undesirable or impractical, although little research data are avail-

Figure 4.—A small patch cutting for paper birch regeneration immediately after cutting. Relatively little seedbed scarification is obtained from logging in this type of opening.

able about such cuttings and they are generally less satisfactory than strips or patches. The first cut should remove 60 percent of the total stand basal area. The residual stand should include four to five paper birch seed trees per acre. All unmerchantable trees down to 1.5 inches d.b.h. should be eliminated at this time. The second cut, after an establishment period of 2 years, should remove the remaining overstory. Heavy cuts (such as the first shelterwood cut) in older stands sometimes result in decadence among residual birch trees, but damage or loss in value is avoided if the second cut is made as soon as the new reproduction is established.

Seedbed preparation.—Seedbed scarification which exposes some mineral soil and mixes it with the humus layers will materially increase the amount of birch regeneration. A scarified seedbed is probably more important than any other factor. Unfortunately, even summer logging normally provides suitable scarification on less than 10 percent of a clearcut area. Scarification from logging in narrow strips often covers a greater proportion of the area if truck roads are laid out to encourage skidding within the strip.

Additional scarification is best achieved through use of a large tractor with dozer blade or rock rake. Great care must be used to avoid removing the humus layer. Alternate raising and lowering of the blade, and backfilling of scraped material with the blade, will usually accomplish the desired result. The goal of scarification should be to expose mineral soil on about 50 percent of the cut area.

The cost of scarification ($15 to $30 per acre) precludes its use on any but the best sites. Scarification should probably be limited to areas with site index of 70 or above. However, the tractor can uproot many of the small unmerchantable trees, thus avoiding the need to remove them with herbicide. As techniques and machinery for scarification improve and costs are reduced, scarification will be justified on many of the better areas. Scarification may be used either in large clearcut areas or in shade-type cuttings.

Direct seeding and planting.—If paper birch seed-producing trees are completely lacking or extremely scarce in the area to be cut and surrounding stands, or if cutting must be done during a poor seed year, it may be necessary to employ direct seeding or planting to obtain paper birch regeneration. As a rule of thumb, four well-distributed paper birch seed-bearing trees per acre should be present to provide adequate natural seedfall during normal seed years.

Because only a small amount of seed can be applied economically in a direct-seeding operation, it is imperative that the seed be sown on a suitable seedbed. Thus scarification should normally be considered along with seeding. If the high cost of scarification

is prohibitive, direct seeding may still be appropriate where the harvest cutting is made in narrow strips to provide a favorable microenvironment and to maximize scarification from the logging. In such cases, seed should be sown only on the areas actually scarified. Scarification may be done any time up to 1 year before seeding.

If paper birch seed is to be stored for more than a few weeks before sowing, it should be stored carefully to avoid loss in viability. After collection, the seed should be spread out in shallow trays to dry at room temperature for about 2 weeks before storage. After drying, the seed should be stored in polyethylene bags or glass jars, tightly sealed, at low temperature. A refrigerator or some other cold-storage facility is ideal and will keep paper birch seed viable for 2 or more years, if necessary.

Paper birch seed should be sown at the rate of at least ½ lb. per acre. It may be sown with a cyclone seeder if mixed with sawdust filler in the ratio of 2 parts sawdust to 1 part seed by volume. Seeding may be done either in the spring (as soon after snowmelt as possible) or in the fall (after leaf fall and before snowfall).

Planting of birch may be considered as an alternative to direct seeding. Although the planted seedlings are sometimes heavily browsed by deer, planting may be more satisfactory than seeding in difficult areas.

INTERMEDIATE STAND CULTURE

Minimum Stocking Requirements

One of the first considerations in placing an existing stand under management is whether or not it contains enough paper birch and other crop-tree species to justify management. Table 1 (appendix) provides some guides to the minimum stocking required for the various management objectives. Those stands that do not meet the minimum stocking requirements should be handled with the northern hardwood or spruce-fir guide, as appropriate.

Cleaning

Cleaning involves the removal of weed species such as pincherry, red maple sprouts, aspen,[1] and striped maple in seedling-or-sapling stands (fig. 5). Individuals of less desirable form may also be removed at this time, regardless of species. This treatment is justified economically only on the best sites where competition

[1]The aspens are considered weed species in many paper birch areas because aspen markets are usually absent or, where present, prices are so low that they preclude effective management for these species. Where they occur in large numbers, aspens are the most serious competitors of paper birch so they should be removed as early in the life of the stand as possible.

Where aspen is to be retained as a crop tree along with paper birch, no attempt should be made to retain longer-lived species, and the aspen and birch should be cleaned or thinned as early as possible to insure survival of the desired stems.

Figure 5.—An aspen is being killed to release the adjacent paper birch crop tree. Thinning in young stands of birch maintains rapid growth and reduces the time required to grow crop trees to desired size.

is expected to reduce the proportion of crop trees below the minimum stocking levels. Cleaning may also be justified in certain scenic or recreation areas where a large proportion of paper birch is desired for its appearance.

Cleaning may be done by cutting or basal spraying the most serious competitors around selected crop trees when the stand is 5 to 10 years old. If sprays are used, care must be taken to avoid herbicide drift and resulting damage to the crop trees. Approximately 150 crop trees should be released per acre. Release of only 150 crop trees is recommended to keep costs to a minimum; this is the minimum number that will be needed when the stand reaches maturity. The purpose of the cleaning is to insure the survival of this minimum number of crop trees when competition is severe. Crop tree specifications are shown in table 2(appendix).

Pruning

Pruning is economically justified only on the best sites and only on yellow birch and sugar maple crop trees. Paper birch and white ash prune naturally at a fast rate and do not need to be pruned if grown in stands of normal density. The value of the other species does not justify pruning. Pruning of sugar maple and yellow birch crop trees should be considered only on the best sites, at the age of 15 to 20 years (before diameter reaches 4 inches). Only the first 17 feet should be pruned. Pruning of paper birch in scenic areas should be limited to removal of dead, broken, or damaged limbs.

Precommercial Thinning

One or two precommercial thinnings between the ages of 25 and 35 years will be required under most circumstances. Such thinnings are needed to mold species composition as desired, to encourage the crown expansion needed to sustain rapid growth during the latter part of the rotation, and to favor trees of highest quality. Although an investment is required, precommercial thinnings provide a higher rate of return than any other silvicultural treatment. They permit significant shortening of the rotation and attainment of maximum yield.

Approximately 250 to 300 paper birch crop trees should be

released per acre. This will provide enough crop trees to form a fully stocked paper birch stand when these trees reach a merchantable size. Where the objective is mixed species, there should be approximately 200 paper birch crop trees and 200 crop trees of longer-lived species. Crop-tree specifications are given in table 2 (appendix).

In some stands, it may not be possible to obtain 250 to 300 paper birch crop trees per acre. In such cases, 150 paper birch crop trees per acre represents about the absolute minimum number required. Stands with fewer paper birch crop trees probably do not warrant precommercial thinnings because there would not be enough paper birch trees to form a fully stocked paper birch stand at maturity.

Trees competing with the crop trees should be removed to give the crop trees ample growing space. However, stocking should not be reduced below the point where the site is fully occupied. (Specific stocking guides are described in the following section). Unwanted trees may be treated with an herbicide, either in frills or with a tree injector.

Commercial Thinnings

Commercial thinnings may begin as soon as the stand attains merchantable size. Initial products will generally be paper birch boltwood and pulpwood of all species. Later thinnings may include some small sawtimber. Thinnings should be planned so as to reduce stand stocking to the level shown in the stocking guide that follows, removing first the non-crop trees, second the trees of lower quality, and third any stems required to improve spatial distribution of the residual trees. Trees with veneer or sawlog grade 1 or 2 potential in the butt log should be retained for the final harvest.

Trees removed in all thinnings will be distributed throughout all crown classes. However, the cut in early thinnings and precommercial thinnings will tend to be concentrated in the upper classes, whereas later thinnings will remove more trees in the lower classes.

Thinning should be timed so that the growth between thinnings

provides enough merchantable volume to support profitable logging. Normally a volume equivalent to about 5 cords is required, depending upon the size and quality of trees removed and the products into which they can be cut.

All thinnings should include the removal of cull trees. Normally there will be very few such trees after the first or second thinning.

Stocking Guides for Thinnings

Although total growth per acre is about equal over a wide range of densities for stands of similar site and species composition, diameter growth of individual trees varies greatly within this density range. Best diameter growth occurs at the lower densities, and maximum stand value is achieved by maintaining the stand at the minimum density required for full site utilization. A stocking guide has been developed, specifying desirable stand densities (in basal area) for stands of various mean diameters and numbers of trees per acre (fig. 8, appendix).

Most unmanaged paper birch stands will be within the vicinity of the A line or above in figure 8. Stands that fall in the area above the A line for a given mean diameter, basal area, and number of trees per acre should be considered overstocked. The B line represents minimum stocking for full occupancy. In thinnings, stands should be cut back to not less than the B line to produce good diameter growth and low mortality. Reducing stocking below the B line provides more growing space than can be utilized, and overall stand growth will be reduced. Stands between the A and B lines usually are adequately stocked. The C line represents the point where 10 years of growth will bring the stand up to the B line. Stands between the B and C lines would therefore be considered slightly understocked; stands below the C line would be definitely understocked.

For example: A stand with a mean diameter of 6 inches, 95 square feet of basal area, and 490 trees per acre is overstocked. By thinning this stand back to the B line (the mean diameter usually remains about the same, although this could be altered),

the stand would then have 61 square feet of basal area and 313 trees per acre. Assuming negligible mortality (number of trees per acre remains the same), the stand would grow and not need to be rethinned until it has reached approximately 104 square feet of basal area and 7.9 inches mean diameter. Growth, of course, slows down as the stand approaches the A line, and the stand may be thinned before it reaches this density.

Some of the stocking concepts used in figure 8 may also be applied to sapling stands. In figure 9, the area above the A line represents overstocked conditions; the area between the A and B lines represents adequate stocking; and the B line itself represents minimum stocking for full size occupancy. Trees at the B line have ample growing space without competition. Thinnings should reduce stocking to this level to produce good diameter growth of the best trees.

Other concepts used in figure 8 are not applicable in sapling stands. The occurrence of stocking levels below the B line does not necessarily result in reduced yield. These small trees are not merchantable, and the loss of a portion of total stand growth is unimportant because this loss would be on trees that would die before they reached merchantable size. As long as the stand contains enough potential crop trees to attain B level stocking when these trees reach merchantable size, the stand may be considered adequately stocked. If a mean stand diameter of 7 inches is about the lower limit of merchantability, approximately 250 to 260 trees would be required. In stands that receive cleanings and/or precommercial thinnings, mortality among the released crop trees is very low, so that the release of 250 to 300 paper birch crop trees will normally be adequate to provide full stocking when these trees reach a merchantable size.

In unmanaged stands (that will not be cleaned or thinned) mortality is often high, and a larger number of acceptable stems are required to insure that there will be enough to make B level stocking when the stand reaches a merchantable size. Stands that are not at least 80 percent stocked (as determined from a stand diagnosis, using procedures shown on page 30) generally need

a cleaning or thinning to insure survival of an adequate number of crop-tree stems.

Schedule of Intermediate Treatments

An idealized schedule of treatments for stands under management from the regeneration phase to maturity is presented in table 4 (appendix). Treatment of stands being placed under management at a later point in the rotation may require a revised schedule to at least partially correct deficiencies resulting from missed treatments. And the entire rotation of such stands may be lengthened. Table 4 represents a general guide for long-term planning. Exact timing of thinnings and other treatments for a particular stand should be determined from the stocking guides and prescriptions rather than from table 4.

HARVEST CUTTINGS

Final harvest cuttings are also regeneration cuttings, and the appropriate type to use depends upon the management objectives and regeneration considerations previously discussed.

Expected rotation ages and sizes are shown for the various species in table 5 (appendix).

Approximate merchantable volume yields in cubic feet per acre from well-stocked stands of various mean diameters are given in table 6 (appendix); the number of years required to reach these volumes are also shown, by site-index classes. Yields for both managed and unmanaged stands are given. Where paper birch is mixed with other species, or where stocking is less than full, the yields for paper birch should be reduced proportionally.

The merchantable volume shown in table 6 is the total volume expected from the final cut. Although specific information is lacking, we estimate that yields from an intensive thinning schedule will produce intermediate yields at least equal to the volumes shown in table 6. For example, under intensive thinning on a site of 70, it would take 56 years to produce a stand of 10 inches average diameter with a volume of roughly 3,830 cubic feet per acre. With thinnings, another 3,830 cubic feet could have been

previously removed, for a total yield of approximately 7,660 cubic feet.

A Management Program for Aesthetics and Other Purposes

Management of paper birch stands for aesthetic purposes, where timber production is secondary or even prohibited, requires cultural measures and schedules quite different from those employed for timber production. Larger expenditures for scarification, weeding, noncommercial thinning, and other measures are justified on these scenic areas to obtain the desired results. And the stocking guides for timber production do not necessarily apply to scenic areas where stocking is determined more by appearance than by maximum growth. Some general guides for stocking and scheduling of treatments are given in tables 1, 4, and 5. Some more specific prescriptions follow. These prescriptions may also have application for paper birch seed-production areas.

In scenic areas, regeneration will normally be obtained in rather small irregularly shaped clearcut patches laid out to fit into the landscape with a pleasing effect. All small trees should be cut and all slash should be removed, burned, or lopped so as to create an acceptable appearance. Seedbed scarification and direct seeding should be used as a means of obtaining large numbers of paper birch from which to develop the desired stand. Stump sprouts are especially important sources of reproduction in scenic areas because of the attractive appearance of birch clumps. Planting of paper birch in such areas may also be considered. Seed-production areas may be started in similar fashion, using larger clearcuttings and seed or seedlings of known origin. Fertilization of seedlings during the first few years may aid in establishment. And it may be desirable to provide protection against deer browsing in certain areas.

At about 5 years of age, the stand should be examined for possible cleaning to remove other species where competition is severe. An early thinning should be possible at about 10 years of age to select and favor those individual paper birch that will

make up the scenic stand. A minimum of 200 trees should be favored at this stage. As many as 400 to 600 should be favored if possible. The bark of the young trees should turn white by 10 years of age to aid this selection of scenic trees. Early thinnings should be light to encourage height growth and good form.

At 15 to 20 years of age, or when the favored trees reach 4 or 5 inches in diameter, a heavy thinning may be made to establish the desired conditions. Additional thinnings may be made to create orchard conditions if desired. Fertilization may be used at age 15 to 20 years or later to stimulate diameter growth or seed production.

On good sites (70 and above), paper birch can be safely grown to about 100 years of age. On poorer sites, a maximum rotation of about 80 years should be the goal.

Management Prescriptions

STAND DIAGNOSIS

Before a prescription can be written for a given stand, a stand diagnosis must be made. The first task is to determine what area will be considered and treated as a separate stand. The area should be small enough so that it will have reasonably similar stand conditions throughout. Site conditions should also be reasonably uniform (a range no greater than one 10-foot site-index class). However, the area should be large enough to efficiently conduct such operations as thinning, cull removal, and harvesting. There is no optimum size: areas may be as small as 1 or 2 acres or as large as can be conveniently laid out and treated.

Once the limits of the stand area have been determined, basal area and number of trees per acre must be determined. In poletimber and larger stands, basal area may be estimated with variable plot-cruising techniques, using a 10-factor prism. To estimate basal area within 10 square feet of the true value, using the 10-factor prism, 1 randomly located sample point is required per acre, up to a maximum of 50 points.

At each sample point, trees counted to determine basal area should be tallied by 2-inch diameter classes. Only trees in the

main crown canopy (dominants, codominants, and intermediates) should be included in these stand measurements. Number of trees per acre may be determined from this tally by multiplying the number of trees in each diameter class by the appropriate conversion value shown on the tally sheet (fig. 10, appendix), and dividing by the number of plots. And basal area per acre is determined by multiplying the average number of trees counted per plot by the prism factor (10).

In addition to basal area and number of trees per acre, it will be necessary to determine paper birch site index. Measurements should be taken on dominant and codominant trees only. Age is determined by increment cores at breast height; total height is obtained by using a Haga altimeter, Abney level, or similar instrument. To estimate total height of the measured trees with acceptable accuracy, at least 10 trees should be measured in stands 50 acres or smaller, or about 1 tree per 5 acres in larger stands; these should be distributed evenly throughout the stand. Site index is then determined from figure 6.

The sample field tally form (fig. 10, appendix) is convenient for recording and summarizing the information needed. Mean diameter and required basal area for stands of that diameter may be read from figure 8. If the stand contains several distinct size classes, decide which one will represent the main stand for future management. Generally this will be the size class with the largest basal area, or the one with the maximum potential. Stand maturity is determined by mean stand diameter, as shown in table 5.

Once completed, the stand-diagnosis tally sheet provides all the information necessary to write a stand prescription.

In young stands (less than 5.0 inches mean diameter), prism cruising cannot be used effectively. The stand measurements required for complete seedling-or-sapling stand diagnosis can be obtained through ordinary plot-cruising techinques. However, a complete diagnosis is not always required in these young stands. It is best to determine site index first; if site is less than 70 in seedling stands or less than 60 in sapling stands, no further stand diagnosis is required because no treatment would be prescribed

in these situations. If site index is higher than that indicated above, a complete stand diagnosis should be made.

To make a complete diagnosis in seedling-and-sapling stands, one randomly located plot is required per acre up to a maximum of 50 plots. The appropriate plot size is one that contains 113 square feet (a circular plot with a radius of 6 feet or a square plot 10.6 feet on each side). Circular plots are easiest to use if a stick cut to the length of the plot radius is used to determine the plot limits.

Field measurements on these plots require a count of the number of potential paper birch crop trees, the number of potential crop trees of other species, and the number of non-crop trees on each plot, recorded by 2-inch diameter classes. From these measurements, number of trees per acre, basal area, and mean stand diameter may be calculated. Stocking is then determined by comparing the observed number of crop trees on each plot with the number required for satisfactory stocking for stands of that diameter, as shown in table 3 (appendix). The proportion of plots that contain the required numbers of crop trees represents the percent stocking of the stand.

A sample field tally form (fig. 11, appendix) is convenient for recording and summarizing the information needed. Site index is measured and the other data are summarized in the same manner as for older stands.

PRESCRIPTIONS

The prescriptions that follow are arranged in the form of a key. Using information obtained from the stand diagnosis, begin at item 1 below and follow the subsequent directions. This will lead you to a prescription describing a specific treatment for the stand.

Item 1. If timber production is one of the primary objectives, see item 2. If production of paper birch for aesthetic purposes is the primary objective, see the recommended silvicultural practices on pages 27 and 28.

Item 2. If the mean stand diameter is—
—less than 1.0 inch, see item 3.

—between 1.0 and 5.0 inches, see item 5.
—between 5.0 and 11.0 inches, see item 8.
—over 11.0 inches, see item 12.

Seedling Stands

Item 3. If the stand is 50 percent or more stocked with paper birch stems, it can be managed appropriately as a paper birch stand under this guide. See item 4. If the stand is less than 50 percent stocked with paper birch stems, use the northern hardwood or spruce-fir guide as appropriate.

Item 4. If the stand is 80 percent or more stocked with paper birch stems, or if total stand stocking is below the A-level in figure 9, see prescription A. If the stand is less than 80 percent stocked with paper birch stems, *and* total stand stocking is above the A-level, see prescription B.

Sapling Stands

Item 5. If the stand is 50 percent or more stocked with paper birch crop trees, it can be managed appropriately as a paper birch stand under this guide. See item 6. If the stand is not 50 percent or more stocked with paper birch crop trees, use the northern hardwood or spruce-fir guide as appropriate.

Item 6. If site index is less than 60, see prescription C. If site index is 60 or more but less than 70, see prescription D. If site index is 70 or more, see item 7.

Item 7. If the management objective is for paper birch boltwood, see prescription E. If the management objective is for saw and veneer logs, see prescription F.

Pole Stands

Item 8. If pole-size and larger paper birch crop trees represent at least 50 percent of B-level stocking (fig. 8), the stand can be managed appropriately as a paper birch stand under this guide. See item 9. If paper birch crop trees do

not represent at least 50 percent of B-level stocking, use the northern hardwood or spruce-fir guide as appropriate.

Item 9. If the paper birch component of the stand is mature for the site and objective (if the average paper birch diameter equals or exceeds the diameters shown in table 5), see item 13. If the paper birch component is not mature, see item 10.

Item 10. If the amount of merchantable basal area above the B level (fig. 8) is sufficient for a commercial cut,[2] the stand should be thinned. See prescription G. If the amount of basal area above the B level is insufficient for a commercial cut, see item 11.

Item 11. If the stand is located on site of index of 60 or more and total stand stocking is above the A level, see prescription H. If the stand is located on site of less than index 60 or if stand stocking is below the A level, see prescription I.

Sawtimber

Item 12. If paper birch represents at least 50 percent of the total basal area, the stand can appropriately be managed under this guide. See item 13. If paper birch represents less than 50 percent of the basal area, use the northern hardwood or spruce-fir guide as appropriate.

Item 13. If the longer-lived crop-tree component of the stand represents at least half of B-level stocking and if these trees are of adequate quality to produce veneer or sawlogs, the paper birch may be harvested and management of the longer-lived species can be continued. See prescription J. If the high-quality longer-lived crop tree component represents less than half of B-level stocking, stocking will not be adequate after the paper birch is

[2]A commercial cut usually requires about 5 cords per acre, which equals 35 square feet of basal area in 6-inch trees, or 20 square feet of basal area in 8-inch trees, or 15 square feet of basal area in 10-inch trees.

harvested. In this case, or in any case where the management objective is for paper birch alone, the entire stand should be harvested and a new one regenerated. See item 14.

Item 14. If there are fewer than four well-distributed paper birch seed trees per acre in the stand to be cut, or if a poor seed crop is expected (based on counts of male catkins), seed supply may be limiting. See prescription K. If the stand to be harvested is located on a south-, southwest-, or west-facing slope in excess of 10 percent, or if it is on a somewhat excessively drained soil, special regeneration measures may be needed to obtain adequate birch regeneration. See prescription L. If site index is less than 55, or if the soil is excessively drained, paper birch will probably not grow well on the site even if established there; other species should be considered for these areas. If none of the above apply, see prescription M.

PRESCRIPTION A. Do nothing now; the stand should develop to the sapling stage satisfactorily without treatment.

PRESCRIPTION B. Paper birch in these stands are under severe competition. On sites of index 70 or above, cleaning is warranted at this time to reduce the competition and insure survival of the favored species. On sites of index less than 70, cleaning is not warranted. Re-examine these stands in 10 years to consider the possibility of an early precommercial thinning.

PRESCRIPTION C. Do nothing now; re-examine the stand at about age 45 to 50, or in 10 years if the stand is already 40 or more years old.

PRESCRIPTION D. A single precommercial thinning is warranted at about age 30 if total stand stocking exceeds the A level. Attempt to release 250 to 300 paper birch crop trees per acre if the management objective is for paper birch alone, or 200 paper birch and 200 other crop trees per acre if the management objective is for mixed timber. Remove all trees competing with the crop trees but do not reduce stocking below the B level.

PRESCRIPTION E. Apply a single precommercial thinning at about 25 years of age. Attempt to release 300 to 400 paper birch trees per acre but do not reduce stocking below B level. A commercial thinning should then be possible in about 15 years. If stocking is below the A level at 25 years of age, the precommercial thinning should be omitted.

PRESCRIPTION F. If stocking is below the A level, postpone the thinning and re-examine the stand in 10 years. Otherwise, apply two precommercial thinnings at about 25 and 35 years of age. Release 250 to 300 paper birch crop trees per acre (minimum 150) if the management objective is paper birch alone or up to 200 paper birch and 200 longer-lived crop trees per acre (minimum of 100 each) if the management objective is mixed timber. Do not reduce stocking below the B level. Sugar maple and yellow birch crop trees in these stands should be considered for pruning.

PRESCRIPTION G. Thin to B level and release enough crop trees to provide B-level stocking of these crop trees alone 10 years hence. The number to release may be determined from figure 8 by assuming that the present crop trees will increase 2 inches in diameter in 10 years. If the management objective is paper birch alone, these crop trees should be all paper birch; if the management objective is mixed timber, these crop trees should be about half paper birch and half long-lived species.

PRESCRIPTION H. Apply a precommercial thinning to reduce stocking to B level. Release enough crop trees to provide B-level stocking of these crop trees alone 10 years hence. The number to release may be determined from figure 8 by assuming that the present crop trees will increase 2 inches in diameter in 10 years. If the management objective is paper birch alone, these crop trees should be all paper birch; if the management objective is mixed timber, these crop trees should be half paper birch and half long-lived species.

PRESCRIPTION I. Do nothing now and re-examine the stand in 10 years. (No thinning is required if stocking is below the A level; and precommercial thinning is not warranted on sites with an index of less than 60.)

PRESCRIPTION J. Paper birch and other merchantable products should be harvested as soon as possible in these stands. Two harvest cuts spaced 5 to 10 years apart will usually be required so that residual density is not reduced below the C level. (Removal of the paper birch will reduce the mean stand diameter considerably so that much less basal area is required for C-level stocking.) Occasionally—when the present stand is not much above the B level—a delay of 5 years or

more may be desirable to build up the basal area enough to permit the first harvest cut without reducing residual stocking below the C level. Where needed, this delay should occur before the first cut rather than between the two cuts because older paper birch often deteriorates after the stand is opened up. After the paper birch has been harvested, the stand should be managed under the northern hardwood or spruce-fir guide, as appropriate.

PRESCRIPTION K. If a reasonably good seed year is not expected, cutting should be postponed until a better seed crop is expected, or the stand should be regenerated by using narrow strip cuttings to optimize the environment and reduce dispersal distances. See pages 16 to 17. If there is a nearly complete lack of paper birch seed trees, direct seeding should be employed in addition to strip cutting. See page 19.

PRESCRIPTION L. Where site conditions are expected to be severe for regeneration, either strip cutting or seedbed scarification, or both, will be required. See pages 16 to 19 for discussion of these techniques.

PRESCRIPTION M. Harvest the present stand and regenerate a new one through clearcutting. If large summer clearcuts are planned, leave about four paper birch seed trees per acre. See pages 13 to 15 for details of procedure.

■

Appendix

Table 1.—*Minimum stocking required for various types of management*[1]

Stand size class	Minimum stocking required[2] for management for—		
	Paper birch timber alone	Mixed timber	Aesthetics or other purposes
Seedlings <1.0 inch mean diameter	At least 50 percent of plots stocked with paper birch stems of any type.	At least 50 percent of plots stocked with paper birch stems and the proportion of crop tree species other than paper birch in the stand is at least 40 percent.	At least 50 percent of plots stocked with paper birch stems.
Saplings 1.0 to 5.0 inches mean diameter	At least 50 percent of plots stocked with paper birch crop trees.	At least 50 percent of plots stocked with paper birch crop trees and the proportion of crop trees other than paper birch in the stand is at least 40 percent.	At least 50 percent of plots stocked with desirable paper birch.
Poles 5.0 to 11.0 inches mean diameter	Paper birch crop trees represent at least 50 percent of B-level basal area. Or, the stand is mature and the management objective calls for regeneration to paper birch.	Paper birch crop trees represent at least 50 percent of B-level basal area and there is an equal number of other (long-lived) crop trees.	At least 100 paper birch trees per acre.
Sawtimber >11.0 inches mean diameter	Stand stocking equals or exceeds C level; paper birch represent at least 50 percent of basal area. Or, the stand is mature and the management objective calls for regeneration to paper birch	Stand stocking equals or exceeds C level; paper birch represents at least 50 percent of basal area, and other crop trees represent at least half of B-level stocking.	At least 50 paper birch trees per acre.

[1]Use northern hardwood or spruce-fir guide as appropriate for stands that do not meet these requirements.

[2]Crop-tree specifications are given in table 2. Stocking of seedling and sapling stands is determined from table 3 and stand diagnosis.

Table 2.—*Crop-tree specifications*

SPECIES AND PRIORITY

Paper birch. (First priority).

Yellow birch, white ash, sugar maple, red spruce, white spruce (Second priority).

Beech, red maple, balsam fir (Third priority).

QUALITY

Trees must have good form and be free of defect, insects, and diseases that will prevent them from developing into merchantable trees of at least grade 2 hardwood sawtimber or into softwood sawtimber or pulpwood. Trees with rotten seams, holes, forks, severe crook in the first 17 feet, damaged or defective crowns, sapsucker injury, or similar defects should not be selected as crop trees. Trees perched on rocks or stumps should be avoided. Rootsuckers and stump sprouts should also be avoided if at all possible.

SIZE

To be eligible for selection as a crop tree in previously unthinned seedling or sapling stands, the tree must have a d.b.h. at least as large as the average stand d.b.h. In other stands, the tree should be in the dominant or codominant crown class (intermediate sugar, maple, beech, or spruce may also be acceptable as crop trees in these stands).

Table 3.—*Number*[1] *of potential paper birch crop trees required in seedling and sapling stands per 113-square-foot plot*[2]

Mean stand diameter (inches)	Number of paper birch required
<0.5	6
0.6–1.5	4
1.6–2.5	3
2.6–3.5	2
3.6–4.5	1

[1]Calculated from tree mortality rates in unmanaged stands on the assumption that desired stocking should be 387 trees at mean stand diameter of 5 inches to correspond to B-level stocking at that diameter as shown in figure 3.

[2]Stocking is the proportion (percentage) of plots that meet requirements shown here. For example, if 82 of 100 plots in a stand of 0.6 to 1.5 inches average diameter have 4 or more paper birch crop-tree stems, the stand is 82 percent stocked.

Table 4.—*Schedule of intermediate treatments*
(At stand age, in years)

Treatment	Management objective									
	Paper birch sawlogs and veneer logs		Paper birch boltwood		Mixed timber of high-value products		Mixed timber of high-value products where clearcutting is not desired		Paper birch for aesthetics	
	Site 70+	Site <70	Site 70+	Site <70	Site 70+	Site <70	Site 70+	Site <70	Site 70+	Site <70
Cleaning	5–10*	—	5–10*	—	5–10*	—	5–10*	—	5	5
Pruning	—	—	—	—	15–20*	—	15–20*	—	(**)	(**)
Precommercial thinning	25	30*	25	30*	25	30*	25	30*	10	10
Precommercial thinning	35	—	—	—	35	—	35	—	15	20
Fertilization	—	—	—	—	—	—	—	—	15	20
Thinning	45	50	35	50	45	50	45	50	(**)	(**)
Thinning	55	60	—	—	55	60	55	60	(**)	(**)
Harvest (paper birch)	65	70	45	60	65	70	65	70	100	80
	Clearcutting, seed tree cutting, or strip cutting		Clearcutting, seed tree cutting, or strip cutting						Small patch cuttings	
Thinning					85	95	85	95		
Thinning					100	115	100	115		
Harvest (other hardwoods or spruce)					120	135	120	135		
					Clearcutting, seed tree cutting, or strip cutting		Patch or shelterwood cuttings			

*Use these cultural treatments only if stand conditions require them. See prescriptions.
**As necessary to maintain health and vigor of trees, prevent insect or disease attack, and maintain appearance desired.

Table 5.—*Expected rotation ages and sizes*[1] *for stands under management*

Species and objective	Paper birch site index (height at b.h. age 50)	Average diameter[2]	Age
	Feet	*Inches*	*Years*
Paper birch, sawtimber	50	9	75
	60	10	70
	70	11	65
Paper birch, boltwood	50	8	65
	60	9	60
	70	9	45
Paper birch, aesthetics	50	9	80
	60	11	90
	70	14	100
Other hardwoods, sawtimber	50	11	135
	60	14	135
	70	15	120
Spruce-fir, pulpwood	50	8	75
	60	8	70
	70	9	65
Spruce only, sawtimber	60	13	135
	70	14	120

[1]See also table 6.
[2]Average diameter of the species shown—not of the entire stand.

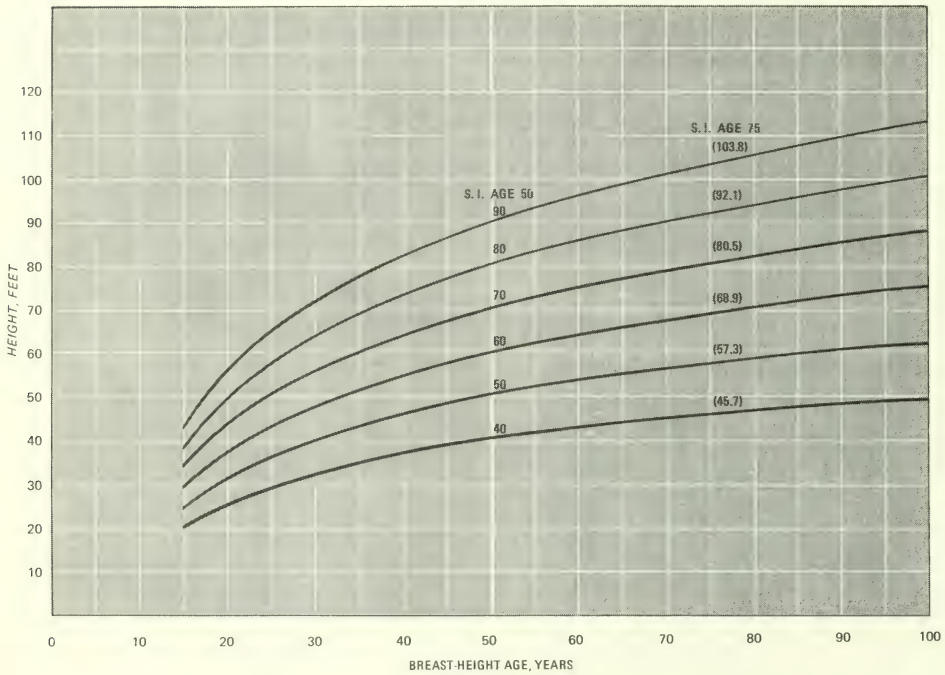
Table 6.—*Merchantable volume yields per acre for stands of various mean diameters, and years to reach various mean diameters by site index (breast height age 50) for pure paper birch stands under intensive thinnings or no thinnings*

Mean diameter[1] (inches)	Merchantable volume per acre[2]	Site index 50		Site index 60		Site index 70	
		Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned
	Cubic feet	*Years*	*Years*	*Years*	*Years*	*Years*	*Years*
5	900	43	34	35	28	27	22
6	1,390	53	42	43	34	33	26
7	1,870	65	52	53	42	38	30
8	2,560	79	63	62	50	47	38
9	3,170	95	76	75	60	58	46
10	3,830	—	89	90	72	70	56
11	4,240	—	—	—	86	85	67

[1]Trees 0.6 inches +.

[2]Merchantable volumes for site index 70. Volumes for other site indices can be calculated by multiplying the above yields by SI/70. Volumes are to a 3- to 5-inch top d.i.b. Yields from an intensive thinning schedule will double yields shown here.

Figure 6.—Site-index curves, based on breast-height age 50, for paper birch in Vermont and New Hampshire. To convert total age to breast-height age for paper birch, subtract 5 years on site <60, 4 years on sites above 60.



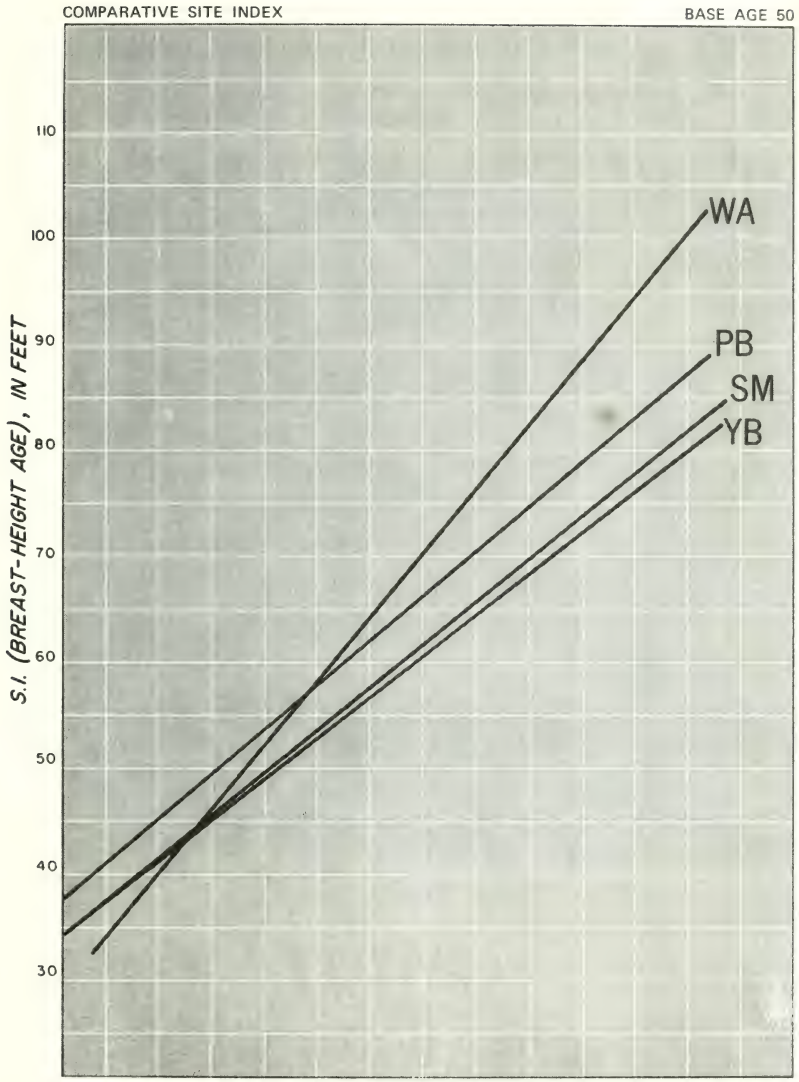


Figure 7.—Relationships among site index for four northern hardwoods. To estimate site index of species X from site index of species Y: find known site index on curve for species Y; move vertically up or down to curve for species X; read horizontally across to the left to find estimated site index for species X.

Figure 8.—Relationship of mean stand diameter to basal area and number of trees per acre for paper birch in the Northeast. The area above the A-line represents overstocked conditions. The area between the A and B lines represents adequate stocking. The area between the B and C lines should be considered as slightly understocked because the stand will return to the B line in 10 years or less. Below the C line is definitely understocked. Only trees in the main crown canopy (dominants, codominants, and intermediates) should be included in stand measurements to be used with this stocking guide.

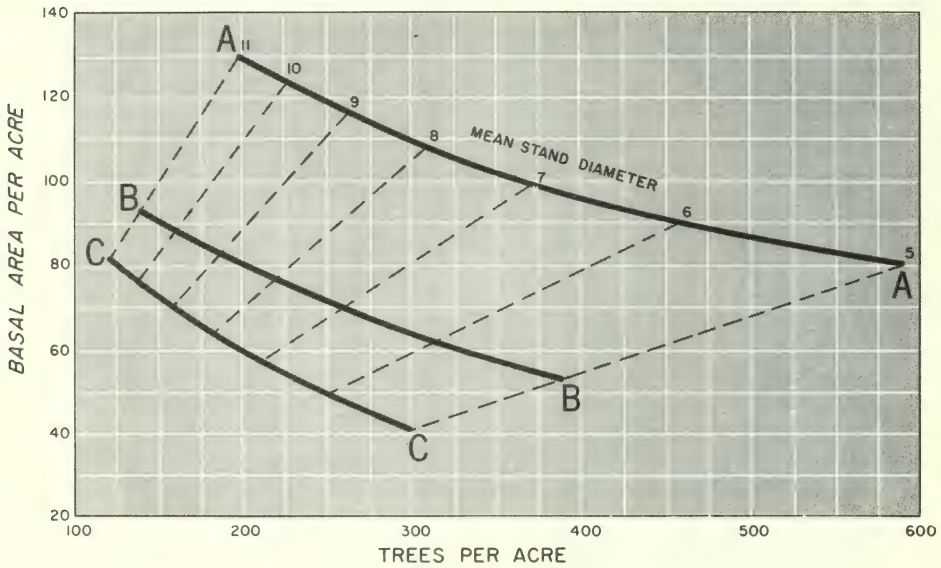
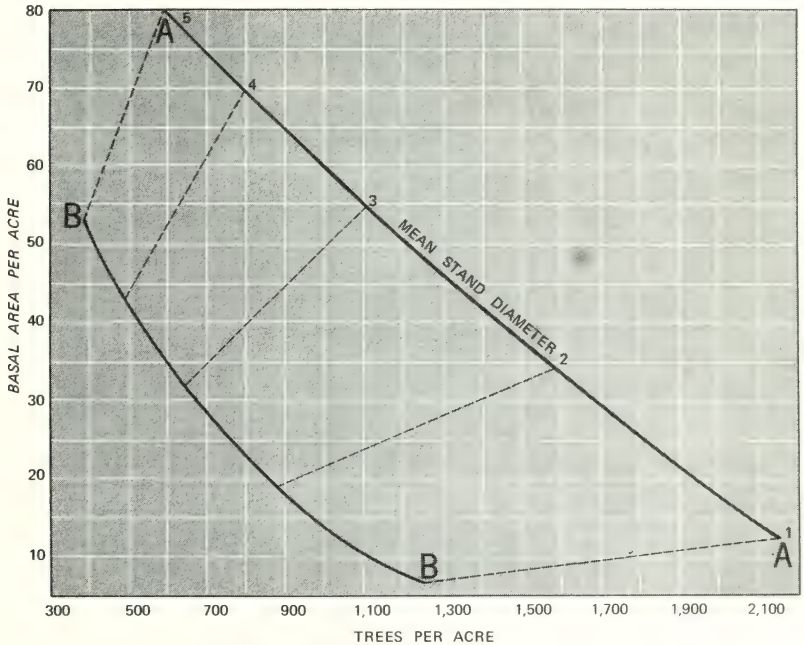


Figure 9.—Relationship of mean stand diameter to basal area and number of trees per acre for paper birch in the Northeast. The area above the A line represents overstocked conditions. The area between the A and B lines represents adequate stocking.



Tally sheet for stand diagnosis

POLE AND SAWTIMBER STANDS

D.b.h. class	Paper birch crop trees[1]	Other crop trees[1]	Non-crop trees[2]	Total	Conversion factor	No. per acre
2					X458 =	
4					X115 =	
6					X51 =	
8					X29 =	
10					X18 =	
12					X12.7 =	
14					X9.4 =	
16					X7.2 =	
18					X5.7 =	
20					X4.6 =	
Total						

Site-index measurements		$\bar{X}$
Height		
Age		

Site index _____

No. of plots sampled _____ Average number trees per plot _____

Average No. of trees per acre _____ Basal area _____ Mean diameter _____

Required basal area: B level _____ C level _____ A level _____

Basal area above B level: _____ (available for cut)

Size class of main stand _____ Stand mature? _____

Management objective: _____

Prescription _____

[1] Trees that meet requirements of table 2 for crop trees, or are merchantable stems of crop-tree species.

[2] Trees that do not meet requirements of table 2 for crop trees, or are unmerchantable even though of merchantable size.

Figure 10.—Sample of tally sheet used for diagnosis of pole and sawtimber stands.

Tally sheet for stand diagnosis

SEEDLING AND SAPLING STANDS

Plot No.	Paper birch crop trees[1]	Other crop trees[1]	Non-crop trees	Total	Stocked ? PB	other
	D.b.h. class <2 2 4 6 8 ε	D.b.h. class <2 2 4 6 8 ε	D.b.h. class <2 2 4 6 8 ε	D.b.h. class <2 2 4 6 8 ε		
Total	(use additional sheets as needed)					
				percent stocked		
Site-index measurements					$\bar{X}$	
Height						
Age						

Site index _____

No. of plots sampled _____

Average No. of trees per acre[2] ____ Basal area per acre[3] ____ Mean diameter[4] ____

Required basal area for: B level _____ A level _____

Basal area above B level _____

Proportion of crop trees that are other than paper birch _____

Management objective: _____

Prescription: _____

[1] Trees that meet requirements of table 3 for crop trees.

[2] Obtained by multiplying the total number of trees observed by 387 and dividing by the number of plots.

[3] Obtained by multiplying total numbers of trees in each diameter class by the appropriate basal area for that size class, summing over all diameter classes, and then multiplying this result by 387 and dividing by the number of plots. For stems <2 inches d.b.h., use the basal area appropriate for 1-inch trees.

[4] Determined from figure 4, using calculated numbers of trees and basal area per acre.

Figure 11.—Sample of tally sheet used for diagnosis of seedling and sapling stands.

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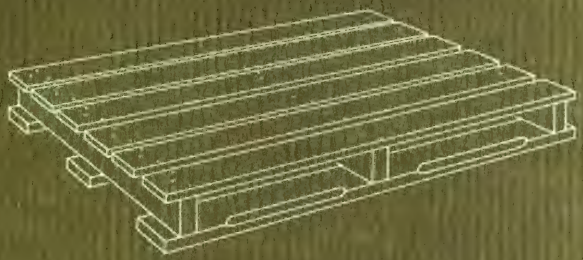
The Department of Defense Market for WOODEN PALLETS: 1967



By John T. Lucas
and Walter B. Wallin

U. S. D. A. FOREST SERVICE RESEARCH PAPER NE-131
1969

NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
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OUR STUDY of the Department of Defense market for wooden pallets in 1967 showed:

- Forty-seven percent fewer pallets were purchased in 1967 than in 1966.
- Plywood pallets were purchased for the first time.
- Nine new pallet specifications were on the DOD list of standard pallet specifications.
- Two temporary distribution areas were set up.

The purpose of our study was to update and supplement the information in "The Department of Defense market for wooden pallets: 1965".[1] Unless otherwise noted, all information relates to 1967 and 1968.

QUALITY AND QUANTITY REQUIREMENTS

The list of Department of Defense (DOD) standard pallet specifications includes 26 different pallet specifications. Each one is designated by a Federal Item Identification Number (FIIN). Nine of the pallet specifications were not on the list in the original report, and three that were listed in the original report in 1965 are no longer classified as standard.

Of the 26 FIIN's, softwood pallets are designated by 8; and

[1] Lucas, John T., and Walter B. Wallin. THE DEPARTMENT OF DEFENSE MARKET FOR WOODEN PALLETS: 1965. U.S. Forest Serv. Res. Paper NE-117. 40 pp. NE. Forest Exp. Sta., Upper Darby, Pa. 1968

hardwood pallets are designated by 18. Eleven of the above FIIN's designate knocked-down pallets (table 1).[2]

DOD updated one pallet specification in 1968. Specification MIL-P-15943B is now designated as MIL-P-15943C.

DGSC purchased 47 percent fewer pallets in 1967 than in 1966. This decrease can be attributed to these factors:

- Hardwood pallets that have been used for the shipment of goods to Vietnam are being reused in Vietnam.
- Many DOD installations built up large inventories of pallets in 1966.
- Many goods that formerly were shipped on pallets are being shipped overseas in skidded plywood containers.
- DOD is purchasing more goods on pallets. Pallets purchased as part of such a unit load are not recorded by DGSC as pallet purchases.

In 1967, 25 of the 26 standard pallets, which are described by 7 different specifications (table 1), were purchased by DGSC (table 2). Six of the pallets (FIIN's 063-9075, 141-7261, 222-1044, 223-6529, 599-5326, and 926-1046) constituted two-thirds of the 1.6 million wooden pallets purchased by DGSC in 1967. Thirty-four percent of the wooden pallets bought by DGSC were softwood units, and 27 percent were knocked-down units (table 2).

DOD has decided that both a post pallet (FIIN 141-7261) and a notched-stringer pallet (FIIN 599-5326) will be designated as primary—the post pallet for overseas shipments and a choice of the post or notched-stringer pallet for domestic shipments. In 1967, 39 percent of the wooden pallets purchased by DGSC were post pallets; and 61 percent were stringer pallets, principally with notched-stringers (table 2). Both of the proposed primary pallets are wing pallets. Seventeen of the 26 FIIN's designate wing pallets, and 82 percent of all pallets purchased by DGSC in 1967 were wing pallets (table 2).

Plywood pallets were purchased by DGSC for the first time in 1967. They were non-standard pallets that conformed to a Civil Defense purchase description.

[2] All tables are in Appendix.

PROCUREMENT AND CONTRACT PERFORMANCE

As of January 1968, 349 firms were listed on the DGSC wooden pallet mailing lists. In 1967, DGSC bought wooden pallets from 49 different firms (table 3). Five firms supplied 47.8 percent of the pallets, and the largest supplier accounted for 13.9 percent. About one-third of the firms that sold wooden pallets to DGSC were in California and North Carolina, nine and seven firms respectively.

Slightly more than three-fourths of all wooden pallets sold to DGSC in 1967 were produced in five states. North Carolina supplied 21.5 percent; Arkansas supplied 16.1 percent; Oregon supplied 15.0 percent; Texas supplied 13.3 percent; and California supplied 11.0 percent (table 3).

All the DGSC wooden pallet purchases in 1967 were from small business firms (500 or fewer employees). Twenty-nine percent of the purchases were from firms in labor surplus areas, and 61 percent were from firms in non-labor surplus areas.

Eighty-seven percent of the wooden pallets were purchased f.o.b. origin, and 13 percent were purchased f.o.b. destination (table 4). Although the terms f.o.b. origin and f.o.b. destination were officially replaced, respectively, by f.o.b. origin (Government Bills of Lading) and f.o.b. origin (freight prepaid to destination by contractor), the original terminology will be used so this report can more easily be compared with the 1965 and 1966 reports.

Because f.o.b. origin shipments predominated, the method of shipment for different kinds of pallets in 1967 differed considerably from that in 1965. F.o.b. origin shipments of pallets purchased by DGSC comprised 91.3 percent of the knocked-down pallets, 84.8 percent of the assembled pallets, 82.1 percent of the softwood pallets, and 88.9 percent of the hardwood pallets (table 4).

Average prices paid for wooden pallets bought f.o.b. origin in 1967 ranged from 51.3 percent lower to 40.1 percent higher than the prices paid in 1966 (table 5). Prices were lower in 1967

than in 1966 for 15 of the 17 kinds of pallets bought f.o.b. origin in both years. And price decreases from 1966 to 1967 were greater than 19 percent for all but five of the pallets.

The percentage range from the low to high f.o.b. origin price (based on the low price) paid for a specific pallet in 1967 varied from a low of 0 percent to a high of 109.6 perecnt (table 6). In 1966 the high was 171.8 percent. The low range was below 50 percent for 20 of the 23 pallets bought f.o.b. origin in 1967. Wooden pallet prices generally decreased throughout the year, but some items increased slightly in the fourth quarter (table 7).

Two temporary distribution areas were set up in 1967—Umatilla and Navajo (fig. 1). They were established mainly to lighten the work load of the original Tracy area.

Prices for most of the pallets supplied from the Richmond region were generally lower than prices for the same pallets supplied from other regions in 1967. Prices were generally higher for pallets supplied from the Memphis, Navajo, and Tracy regions (table 8 and fig. 1).

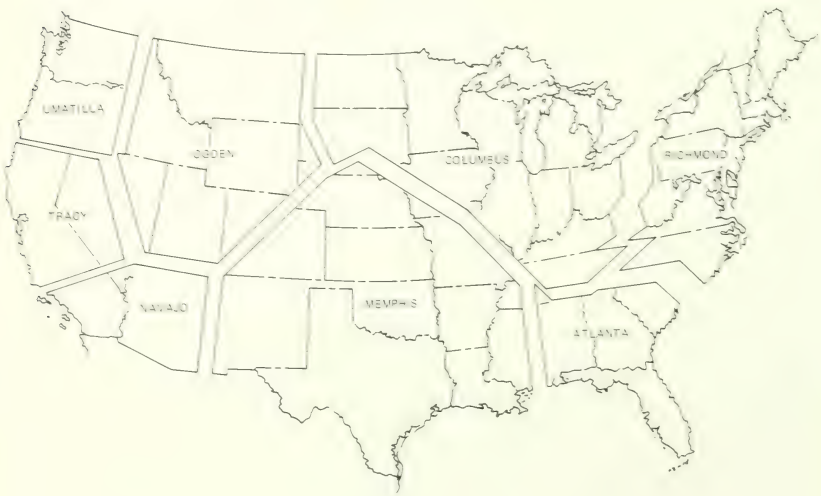

Figure 1. — DGSC distribution areas in the United States.

WHERE AND WHEN THE PALLETS ARE NEEDED

In 1967, DGSC received requisitions for 2,607,559 wooden pallets from DOD and purchased 1,611,156.

The Armed Forces needed 83.8 percent of the wooden pallets bought by DGSC in 1967. Most of the wooden pallets were needed by the Army (53.6 percent), followed by the Navy (27.3 percent), the Marine Corps (1.6 percent), and the Air Force (1.3 percent). Other sources of demand—the Coast Guard, General Services Administration, and the Military Assistance Program—needed 16.2 percent of the pallets (table 9).

More pallets were required in January (11.4 percent) than in any other month in 1967 (table 10). Monthly pallet demand was more constant in 1967 than in 1965 or 1966. December was the only month in which demand was considerably below the average monthly demand for the year.

More pallets (31.5 percent) were required by installations in the Richmond region than in any other region. Installations in the Tracy region required the next largest proportion of pallets (26.2 percent) (table 11). As in 1966, most of the knocked-down pallets were required by the Tracy and Richmond regions (82.8 percent). But the demand pattern for softwood pallets in 1967 was different from that in 1966. Only 41.4 percent of the softwood pallets were required by the Tracy and Richmond regions (table 11).

■

APPENDIX

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Table 1. — *Standard DOD wooden pallets*

Federal Item Identification Number (FIIN)[1]	Specification or purchase description number	Assembled (A) or knocked-down (Kd)[2]	Type of lumber[3]	Dimensions (inches)	Number and type of deck supports	Entry	Sides
063-9075*	NN-P-71b	A	Softwood	40X48	3 stringers	2-way	Double wing
141-7237	MIL-P-15011F	A	Softwood	40X48	9 posts	4-way	Flush
141-7261*	MIL-P-15011F	A	Hardwood	40X48	9 posts	4-way	Double wing
141-7262	MIL-P-4894	A	Softwood	40X48	3 stringers	2-way	Flush
202-2217	MIL-P-15943C	A	Hardwood	48X72	3 stringers	2-way	Double wing
222-1044*	NN-P-71b	A	Hardwood	48X60	5 stringers	2-way	Flush
222-1046	NN-P-71b	A	Hardwood	32X40	3 stringers	2-way	Flush
222-1048	NN-P-71b	Kd	Hardwood	32X40	3 stringers	2-way	Flush
222-1051	NN-P-71b	Kd	Hardwood	48X60	5 stringers	2-way	Flush
222-1053	MIL-P-15943C	Kd	Hardwood	48X72	3 stringers	2-way	Double wing
223-6529*	MIL-P-15011F	Kd	Hardwood	40X48	9 posts	4-way	Double wing
291-8717	NN-P-71b	Kd	Hardwood	40X48	3 stringers	2-way	Flush
542-3294	MIL-P-22562	A	Hardwood	32X40	3 notched stringers	Partial 4-way	Double wing
555-0458	NN-P-71b	A	Hardwood	40X48	3 stringers	2-way	Flush

599-5326*	MIL-P-3938B	A	Hardwood	40X48	4 notched stringers	Partial 4-way	Double wing
781-1983	NN-P-71b	Kd	Hardwood	40X48	3 stringers	2-way	Flush
892-4394	MIL-P-43465(GL)	Kd	Softwood	57X32¼	3 notched stringers	Partial 4-way	Double wing
892-4395	MIL-P-43465(GL)	Kd	Softwood	44X31⅜	3 notched stringers	Partial 4-way	Double wing
926-1046*	MIL-P-15011F	A	Hardwood	40X48	9 posts	4-way	Double wing
926-1047	MIL-P-3938B	A	Hardwood	40X48	4 notched stringers	Partial 4-way	Double wing
926-1048	MIL-P-3938B	Kd	Hardwood	40X48	4 notched stringers	Partial 4-way	Double wing
926-3748	MIL-P-15943C	Kd	Softwood	48X72	3 stringers	2-way	Double wing
926-3808	MIL-P-15011F	A	Softwood	40X48	9 posts	4-way	Double wing
926-3848	NN-P-71b	Kd	Softwood	40X48	3 stringers	2-way	Double wing
946-2963	MIL-P-15943C	A	Hardwood	48X72	3 stringers	2-way	Double wing
959-0743	NN-P-71b	A	Hardwood	48X48	3 stringers	2-way	Double wing

[1] The six kinds of pallets designated by an asterisk (*) beside the FIIN's constituted two-thirds of the number of standard pallets purchased by DGSC in 1967.

[2] The knocked-down category refers to parts for pallets that are packaged for shipment to a DOD installation, generally overseas, where fabrication takes place. All but two are shipped in bundles containing parts for 20 pallets; FIIN's 222-1053 and 926-3748 require parts bundled for one pallet only.

[3] Some DOD specifications and purchase descriptions allow only certain species for pallet construction—in several instances, low-density broadleaf species are classified as "softwoods".

Table 2. — *Wooden pallets purchased by DGSC in 1967, by Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	Number of pallets[2]	Percent
†063-9075	370,074	22.97
141-7261	218,713	13.57
223-6529	158,540	9.84
926-1046	157,500	9.78
599-5326	89,561	5.56
222-1044	83,384	5.18
291-8717	73,840	4.58
†926-3808	62,439	3.88
555-0458	57,327	3.56
†926-3848	55,260	3.43
†892-4394	44,100	2.74
959-0743	36,645	2.27
926-1048	30,720	1.91
926-1047	25,526	1.58
222-1046	24,273	1.51
222-1053	23,079	1.43
202-2217	22,458	1.39
222-1048	20,100	1.25
542-3294	15,663	.97
†141-7237	13,036	.81
222-1051	10,680	.66
†892-4395	8,380	.52
781-1983	6,160	.38
946-2693	2,393	.15
†141-7262	1,305	.08
All pallets	1,611,156	100.00

[1] See table 1 for descriptions of the pallets.

[2] In addition to the total for this column, DGSC purchased 155,614 non-standard lumber pallets and 17,550 non-standard plywood pallets.

† Softwood pallets.

Table 3. — *Wooden pallets supplied in 1967, by states and firms*

State	Number of firms	Number of pallets	Percent of pallets
North Carolina	7	346,832	21.53
Arkansas	4	259,268	16.09
Oregon	2	241,694	15.00
Texas	2	213,857	13.27
California	9	177,110	10.99
Washington	3	108,820	6.76
Alabama	3	82,369	5.11
Tennessee	3	50,123	3.11
Maryland	4	42,963	2.67
Mississippi	2	37,794	2.35
Virginia	4	25,576	1.59
Colorado	1	9,500	.59
Hawaii	2	8,500	.53
Pennsylvania	1	3,900	.24
Georgia	1	1,850	.11
Kentucky	1	1,000	.06
Total	49	1,611,156	100.00

Table 4. — *Wooden pallets purchased by DGSC in 1967, by type of shipment and Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	F.o.b. origin		F.o.b. destination		Total pallets purchased
	Number	*Percent*	*Number*	*Percent*	*Number*
†063-9075	370,074	100.00	—	—	370,074
141-7261	218,213	99.77	500	.23	218,713
223-6529	158,540	100.00	—	—	158,540
926-1046	157,500	100.00	—	—	157,500
599-5326	89,561	100.00	—	—	89,561
222-1044	55,470	66.52	27,914	33.48	83,384
291-8717	71,800	97.24	2,040	2.76	73,840
†926-3808	—	—	62,439	100.00	62,439
555-0458	28,220	49.23	29,107	50.77	57,327
†926-3848	55,260	100.00	—	—	55,260
†892-4394	16,960	38.46	27,140	61.54	44,100
959-0743	22,260	60.74	14,385	39.26	36,645
926-1048	30,720	100.00	—	—	30,720
926-1047	—	—	25,526	100.00	25,526
222-1046	10,420	42,93	13,853	57.07	24,273
222-1053	23,079	100.00	—	—	23,079
202-2217	20,433	90.98	2,025	9.02	22,458
222-1048	19,700	98.01	400	1.99	20,100
542-3294	13,988	89.31	1,675	10.69	15,663
†141-7237	11,446	87.80	1,590	12.20	13,036
222-1051	10,680	100.00	—	—	10,680
†892-4395	400	4.77	7,980	95.23	8,380
781-1983	6,160	100.00	—	—	6,160
946-2693	2,393	100.00	—	—	2,393
†141-7262	1,200	91.95	105	8.05	1,305
All FIIN's	1,394,477	86.55	216,679	13.45	1,611,156

[1] See table 1 for descriptions of the pallets.

† Softwood pallets.

Table 5. — *Average f.o.b. origin wooden pallet prices, 1966-1967 by Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	1966	1967	Change in price 1966-1967
			Percent
†063-9075	$ 2.68	$ 2.59	−3.4
†141-7237	3.58	2.70	−24.6
141-7261	4.51	3.56	−21.1
†141-7262	([2])	9.35	—
202-2217	16.87	11.66	−30.9
222-1044	([3])	4.63	—
222-1046	1.92	2.69	+40.1
222-1048	3.37	2.35	−30.3
222-1051	6.86	4.89	−28.7
222-1053	25.30	12.31	−51.3
223-6529	6.06	4.07	−32.8
291-8717	4.97	4.50	−9.4
542-3294	2.88	2.16	−25.0
555-0458	3.71	2.86	−22.9
599-5326	4.61	3.17	−31.2
781-1983	([2])	4.18	—
†**892-4394**	3.54	2.86	−19.2
†**892-4395**	3.02	3.30	+19.3
926-1046	5.15	3.87	−24.8
†926-1047	4.31	([3])	—
926-1048	([2])	3.72	—
†926-3808	([2])	([3])	—
†**926-3848**	([2])	2.28	—
946-2693	([2])	11.11	—
959-0743	4.00	3.53	−11.8

[1] See table 1 for description of the pallets.

[2] No pallets were purchased.

[3] All pallets were purchased f.o.b. destination.

† Softwood pallets.

Table 6. — *F.o.b. origin wooden pallet prices, 1967, by Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	Average price	Price range	Price range
			Percent of low price
†063-9075	$ 2.59	$ 2.39-2.79	16.7
†141-7237	2.70	2.62-3.25	24.0
141-7261	3.56	3.20-3.88	21.3
†141-7262	9.35	9.35-9.35	0
202-2217	11.66	9.93-14.23	43.3
222-1044	4.63	3.85-5.95	54.5
222-1046	2.69	2.25-3.29	46.2
222-1048	2.35	2.10-3.00	43.9
222-1051	4.89	4.76-5.00	5.0
222-1053	12.31	10.60-22.22	109.6
223-6529	4.07	3.61-4.68	29.6
291-8717	4.50	2.68-4.92	83.6
542-3294	2.16	2.00-4.19	109.5
555-0458	2.86	2.61-3.35	28.4
599-5326	3.17	2.78-3.95	42.1
871-1983	4.18	3.24-4.34	34.0
†**892-4394**	2.86	2.73-3.73	36.6
†**892-4395**	3.30	3.30-3.30	0
926-1046	3.87	3.57-4.38	22.7
926-1048	3.72	3.39-3.73	10.0
†**926-3848**	2.28	2.27-2.29	9
946-2693	11.11	10.01-11.83	18.2
959-0743	3.53	3.10-4.60	48.4

[1] See table 1 for descriptions of the pallets.

† Softwood pallets.

Table 7. — *Average f.o.b. origin wooden pallet prices, 1967, by quarter of the year and Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	1 January-March	2 April-June	3 July-September	4 October-December	Average
†063-9075	$ 2.72	$ 2.52	$ 2.72	—	$ 2.59
†141-7237	2.62	—	2.88	$ 2.85	2.70
141-7261	—	3.55	3.71	3.42	3.56
†141-7262	—	—	9.35	—	9.35
202-2217	14.23	—	11.53	11.68	11.66
222-1044	5.14	4.58	4.79	4.30	4.63
222-1046	2.77	—	—	2.44	2.69
222-1048	2.86	2.65	2.12	—	2.35
222-1051	4.89	—	—	—	4.89
222-1053	16.27	13.53	11.46	11.73	12.31
223-6529	4.40	4.09	—	3.74	4.07
291-8717	4.81	3.10	2.70	2.83	4.50
542-3294	4.19	2.16	—	2.00	2.16
555-0458	3.31	2.91	2.72	2.85	2.86
599-5326	—	—	3.93	3.02	3.17
781-1983	4.34	3.44	3.56	3.64	4.18
†892-4394	2.85	3.08	—	—	2.86
†892-4395	3.30	—	—	—	3.30
926-1046	3.85	4.02	3.73	—	3.87
926-1048	—	3.71	3.72	—	3.72
†926-3848	—	—	—	2.28	2.28
946-2693	—	—	10.01	11.83	11.11
959-0743	—	3.79	3.50	3.31	3.53

[1] See table 1 for descriptions of the pallets.

† Softwood pallets.

Table 8. — *Average f.o.b. origin wooden pallet prices, 1967, by geographical region of the suppliers and Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	Region[2]								Average
	Richmond	Atlanta	Memphis	Columbus	Ogden	Tracy	Navajo	Umatilla	
†063-9075	—	—	—	—	—	—	$ 2.70	$ 2.56	$ 2.59
†141-7237	$ 3.25	—	—	—	—	$ 2.89	—	2.65	2.70
141-7261	3.38	$ 3.59	$ 3.58	—	—	—	—	—	3.56
†141-7262	—	—	—	—	—	—	—	9.35	9.35
202-2217	11.51	—	11.53	—	—	—	12.70	—	11.66
222-1044	4.53	—	4.55	—	—	5.95	—	—	4.63
222-1046	2.40	2.62	2.82	—	—	—	—	—	2.69
222-1048	2.47	2.14	—	—	—	—	—	—	2.35
222-1051	—	—	4.89	—	—	—	—	—	4.89
222-1053	11.75	14.48	14.60	$11.57	—	—	—	—	12.31
223-6529	4.01	4.13	4.40	—	—	—	—	—	4.07
291-8717	3.31	2.76	4.92	—	—	4.80	6.95	—	4.50
542-3294	2.10	—	2.15	—	—	—	4.19	—	2.16
555-0458	2.85	2.91	2.87	—	—	—	—	—	2.86
599-5326	3.94	—	2.78	—	—	—	—	—	3.17
781-1983	3.60	4.22	—	—	—	—	—	—	4.18
†892-4394	2.73	—	—	—	—	3.73	—	3.18	2.86
†892-4395	—	—	—	—	—	3.30	—	—	3.30
926-1046	4.38	3.57	3.89	—	—	—	—	—	3.87
922-1048	—	3.70	3.73	—	—	—	—	—	3.72
†926-3848	—	—	—	—	—	2.27	—	2.29	2.28
946-2693	10.01	11.83	—	—	—	—	—	—	11.11
959-0743	3.53	3.27	3.76	—	—	—	—	—	3.53

[1] See table 1 for descriptions of the pallets.
[2] See figure 1 for regional boundaries.
† Softwood pallets.

Table 9. — *Number of wooden pallets demanded in 1967, by service branch and Federal Item Identification Number*
(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	Service branch						Percent
	Army	Navy	Air Force	Marine Corps	Other[2]	Total	
†063-9075	287,727	35,465	1,433	9,957	48,884	383,466	14.70
†141-7237	—	—	7,948	—	—	7,948	.30
141-7261	285,532	229,105	21,356	895	162,207	699,095	26.81
202-2217	28,787	9,800	—	—	—	38,587	1.48
222-1044	25,728	—	—	—	62,800	88,528	3.40
222-1046	17,734	—	700	—	—	18,434	.71
222-1048	7,800	—	—	—	—	7,800	.30
222-1051	4,960	—	—	—	—	4,960	.19
222-1053	6,171	—	7	—	—	6,178	.24
223-6529	240,280	—	—	—	—	240,280	9.21
291-8717	16,600	—	—	—	—	16,600	.64
542-3294	—	957	—	12,062	—	13,019	.50
555-0458	54,991	—	—	—	1,960	56,951	2.18
599-5326	258,983	257,536	720	13,809	133,737	664,785	25.49
781-1983	1,260	—	—	—	—	1,260	.05
†**892-4394**	98,300	—	—	—	2,000	100,300	3.85
†**892-4395**	1,520	—	—	—	2,660	4,180	.16
†**926-3748**	1,890	—	—	—	—	1,890	.07
†926-3808	—	156,158	—	—	—	156,158	5.99

CONTINUED

Table 9. — Continued

Federal Item Identification Number (FIIN)[1]	Service branch						Percent
	Army	Navy	Air Force	Marine Corps	Other[2]	Total	
†926-3848	55,260	—	—	—	—	55,260	2.12
946-2693	—	3,393	—	—	—	3,393	.13
955-9632	2,050	—	—	—	—	2,050	.08
956-2950	1,000	—	—	—	—	1,000	.04
959-0743	450	18,382	2,500	4,538	9,567	35,437	1.36
Total	1,397,023	710,796	34,664	41,261	423,815	2,607,559	100.00
Percent	53.58	27.26	1.33	1.58	16.25	100.00	—

[1] See table 1 for descriptions of the pallets.
[2] Coast Guard, Military Assistance Program, GSA, and others.
† Softwood pallets.

Table 10. — *Number of wooden pallets demanded in 1967, by month and Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	January	February	March	April	May	June	July	August	September	October	November	December	Total	Percent
†063-9075	—	227,886	22,000	6,861	21,670	31,858	61,363	294	650	5,000	884	5,000	383,466	14.70
†141-7237	86	—	—	—	5,400	642	—	300	1,520	—	—	—	7,948	.30
141-7261	73,699	37,874	72,541	31,116	55,254	69,768	57,456	29,842	113,750	40,551	110,583	6,661	699,095	26.81
202-2217	1,254	—	—	400	16,012	1,060	4,430	2,331	—	3,100	3,000	7,000	38,587	1.48
222-1044	3,336	3,204	10,640	29,864	1,706	1,843	20,300	6,335	1,000	7,500	1,300	1,500	88,528	3.40
222-1046	1,574	1,440	1,223	1,681	740	1,866	219	3,055	1,694	919	1,600	2,423	18,434	.71
222-1048	1,100	260	—	6,260	100	—	—	—	—	—	—	80	7,800	.30
222-1051	20	—	—	—	—	—	—	2,440	120	2,000	—	380	4,960	.19
222-1053	7	—	40	72	1,825	4,034	—	200	—	—	—	—	6,178	.24
223-6529	104,760	40	—	11,000	40	80	—	124,360	—	—	—	—	240,280	9.21
291-8717	8,000	4,380	100	—	1,000	—	—	140	—	1,760	—	1,220	16,600	.64
542-3294	200	—	—	7,486	195	—	1,107	198	3,332	—	501	—	13,019	.50
555-0458	10,764	280	150	11,720	800	3,388	50	2,910	2,379	2,980	9,260	12,270	56,951	2.18
599-5326	89,800	12,520	93,168	77,234	43,087	91,496	78,290	46,261	39,075	24,347	51,866	17,641	664,785	25.49
781-1983	—	500	400	—	—	50	—	50	12	148	100	—	1,260	.05
†892-4394	3,120	5,280	1,440	5,780	4,860	15,680	13,420	6,020	8,080	13,560	16,680	6,380	100,300	3.85
†892-4395	680	—	60	—	300	540	500	—	1,500	100	40	460	4,180	.16
†926-3748	—	—	—	—	—	—	—	—	—	—	—	1,890	1,890	.07
†926-3808	—	—	—	—	—	—	—	—	—	124,877	31,281	—	156,158	5.99
†926-3848	—	—	—	—	—	—	—	—	55,260	—	—	—	55,260	2.12
946-2693	—	—	—	—	2,950	443	—	—	—	—	—	—	3,393	.13
955-9632	—	—	—	50	—	—	—	—	2,000	—	—	—	2,050	.08
956-2950	—	—	—	—	—	—	—	500	—	—	—	500	1,000	.04
959-0743	—	200	10,000	300	9,476	5,000	4,238	2,750	—	473	3,000	—	35,437	1.36
Total	298,400	293,864	211,762	189,824	165,415	227,748	241,373	227,986	230,372	227,315	230,095	63,405	2,607,559	100.00
Percent	11.44	11.27	8.12	7.28	6.34	8.73	9.26	8.74	8.84	8.72	8.83	2.43	—	—

[1] See table 1 for descriptions of the pallets.

† Softwood pallets.

Table 11. — *Number of wooden pallets demanded in 1967, by location and Federal Item Identification Number*

(Numbers in boldface indicate knocked-down pallets)

Federal Item Identification Number (FIIN)[1]	Location[2]												Total	Percent
	Atlanta[3]	Norfolk[4]	Oakland[5]	Tracy[6]	Columbus[7]	Memphis[8]	Richmond[9]	Ogden[10]	Mechanicsburg[11]	Umatilla[12]	Navajo[13]	Not specified		
†063-9075	6,000	11,387	50	—	288,982	1,727	19,858	48,884	—	6,578	—	—	383,466	14.70
†141-7237	56	—	—	7,662	—	—	—	230	—	—	—	—	7,948	.30
141-7261	74,071	28,698	4,683	84,887	37,426	60,019	331,942	49,922	22,165	4,312	—	970	699,095	26.81
202-2217	84	3,600	—	22,455	—	100	6,148	—	200	2,400	3,600	—	38,587	1.48
222-1044	3,350	—	—	12,743	3,042	40,758	1,844	21,800	3,420	1,571	—	—	88,528	3.40
222-1046	212	—	—	3,734	2,450	8,074	3,714	100	150	—	—	—	18,434	.71
222-1048	—	—	—	100	—	160	7,540	—	—	—	—	—	7,800	.30
222-1051	340	—	—	20	80	—	4,520	—	—	—	—	—	4,960	.19
222-1053	—	—	—	5,559	—	—	119	—	—	500	—	—	6,178	.24
223-6529	—	—	—	226,560	—	300	2,420	—	—	11,000	—	—	240,280	9.21
291-8717	—	—	—	3,360	—	—	13,240	—	—	—	—	—	16,600	.64
542-3294	89	—	3,983	7,567	—	—	405	—	—	—	975	—	13,019	.50
555-0458	171	—	—	30,773	4,200	2,295	16,232	2,160	1,120	—	—	—	56,951	2.18
599-5326	97,673	3,000	16,416	76,965	34,194	106,931	173,081	66,547	71,123	17,253	32	1,570	664,785	25.49
781-1983	—	—	—	1,210	—	50	—	—	—	—	—	—	1,260	.05
†892-4394	9,920	—	—	35,500	5,220	41,900	4,240	—	480	3,040	—	—	100,300	3.85
†892-4395	100	—	—	—	2,540	520	1,020	—	—	—	—	—	4,180	.16
†926-3748	—	—	—	1,890	—	—	—	—	—	—	—	—	1,890	.07
†926-3808	—	19,000	75,877	—	—	—	61,281	—	—	—	—	—	156,158	5.99
†926-3848	—	—	—	55,260	—	—	—	—	—	—	—	—	55,260	2.12
946-2693	—	400	2,000	550	—	—	443	—	—	—	—	—	3,393	.13
955-9632	—	—	—	—	50	2,000	—	—	—	—	—	—	2,050	.08
956-2950	—	—	—	—	—	—	1,000	—	—	—	—	—	1,000	.04
959-0743	12,053	4,382	—	4,801	12,000	—	2,201	—	—	—	—	—	35,437	1.36
Total	204,119	70,467	103,009	581,596	390,184	264,834	651,248	189,643	98,658	46,654	4,607	2,540	2,607,559	—
Percent	7.83	2.70	3.95	22.30	14.96	10.16	24.98	7.27	3.78	1.79	0.18	0.10	—	100.00

[1] See table 1 for descriptions of the pallets.
[2] See figure 1 for the regional boundaries.
[3] Atlanta Army Depot, Forest Park, Ga.
[4] Naval Supply Center, Norfolk, Va.
[5] Naval Supply Center, Oakland, Calif.
[6] Defense Depot Tracy, Tracy, Calif.
[7] Defense Construction Supply Center, Columbus, Ohio.
[8] Defense Depot Memphis, Memphis, Tenn.
[9] Defense General Supply Center, Richmond, Va.
[10] Defense Depot Ogden, Ogden, Utah.
[11] Mechanicsburg Depot, Mechanicsburg, Pa.
[12] Temporary depot, Umatilla, Oregon.
[13] Temporary depot, Navajo, N. Mex.
† Softwood pallets.

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Use of WOODEN PALLETS in the Brewing Industry

by John T. Lucas

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Use of
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INTRODUCTION

LARGE quantities of wooden pallets are used by many industries. These pallets are used to stack material for handling, transporting, and storage.

Because many pallet suppliers have limited knowledge of the actual or potential market in any particular industry, the U. S. Forest Service undertook the study described below. The brewing industry was selected because it provides a large present market and a potentially greater future market for wooden pallets.

The objectives of the study were to analyze the market in terms of: (1) location and characteristics of the industry, (2) pallet-purchasing practices, (3) types of pallets in use, (4) pallet life and repair, (5) palletized handling systems, and (6) the future role of wooden pallets in the industry.

The study consisted of personal interviews with materials-handling officials in nine large U. S. breweries. These nine breweries accounted for 58 percent of the volume of domestic brewery products in 1966 *(Sanchagrin 1968)*.

LOCATION & CHARACTERISTICS OF THE INDUSTRY

Ninety-nine breweries were authorized by the Internal Revenue Service to operate in the United States in 1967. These breweries managed 157 plants in 31 different states (fig. 1).

There is a trend toward greater concentration in the brewery industry. In the last decade U. S. brewery products sales increased about 28 percent while the number of brewing plants decreased about 38 percent *(Crivella 1965, U. S. Brewers Assoc. 1967)*. The sales increase has been accounted for entirely by packaged brewery products. Kegged brewery products sales have changed little during the last decade (fig. 2).

In the past few years the largest breweries have been increasing their market share and probably will continue to do so in the future. In 1967 the 25 largest breweries sold 91.5 percent of the U. S. brewery products, and the 3 largest breweries sold 33.1

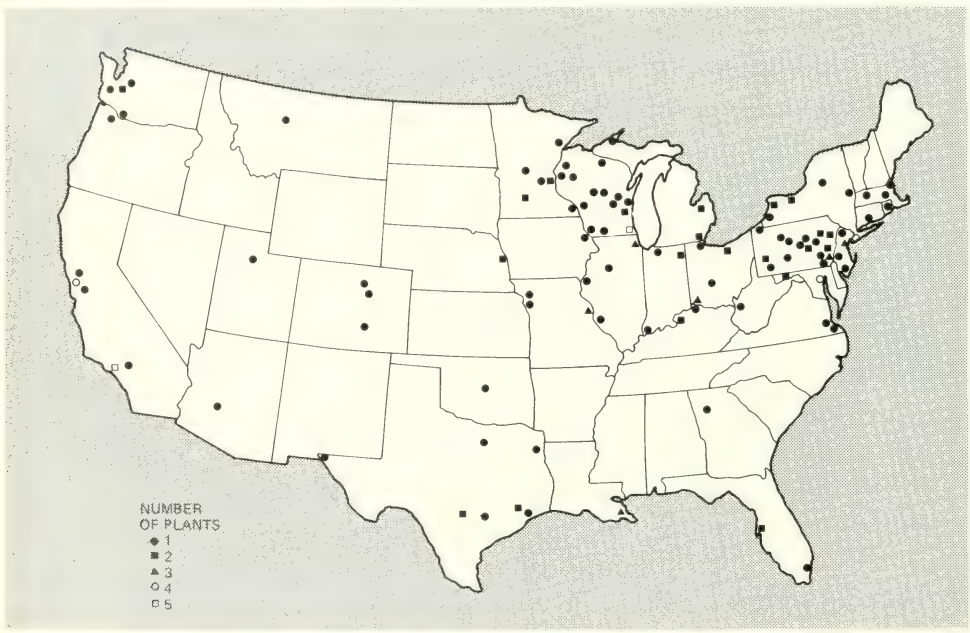
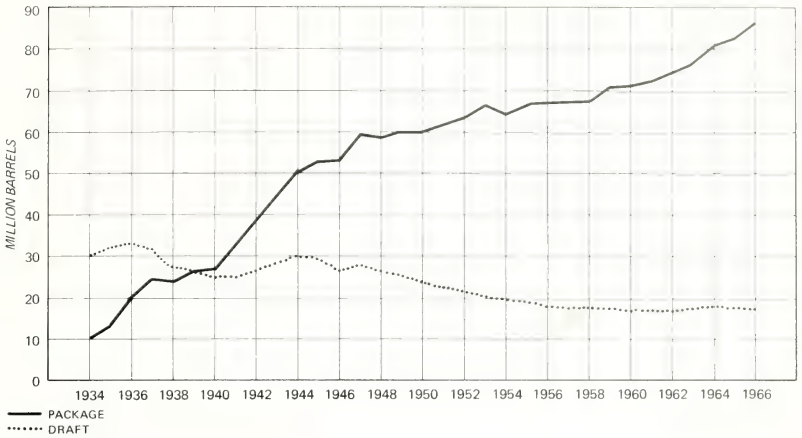


Figure 1.—Brewing plants authorized to operate in the United States as of July 1, 1967. Two other plants not shown are located in Hawaii.

Figure 2.—Draft and package sales of malt beverages for calendar years 1934 to 1966. (One barrel = 31 gallons.)



percent *(Sanchagrin 1968)*. Smaller breweries are being liquidated or merged because, in many instances, they cannot afford to modernize facilities and techniques enough to operate profitably in this highly competitive industry *(Crivella 1965)*.

PALLET PURCHASING PRACTICES

All the breweries surveyed were using wooden pallets. The earliest date that any of them started using wooden pallets in their main plant was 1949; the latest date was 1962. Some breweries experimented with wooden pallets in field plants before introducing them into the handling program of the main plant. Others did the initial testing in the main plant. Many breweries are conducting in-plant pallet-test programs to improve pallet design and style.

The main plant of some breweries is responsible for supplying pallets to all the other plants operated by the brewery. Other breweries allow the purchasing department within each plant to buy pallets locally. Sometimes, when pallets can be bought locally, the main plant must approve the source of supply.

Contrary to the practice of some industries, breweries buy practically all the pallets they use. Only one of the study brewer-

ies had made any pallets, other than experimentally, for its own use, and these were for a government order calling for fewer than 100 pallet-loads of brewery products. One study brewery did rent pallets, but the practice was discontinued.

When a brewery purchasing agent desires to buy wooden pallets, he usually asks for bids from pallet firms that are on a list of approved suppliers maintained by the brewery. The pallet suppliers are generally located within several miles of the brewery, and close working relationships generally exist between the suppliers and the brewery—in much the same manner as pallet suppliers and steel plants *(Carlson 1966)*.

Seven of the nine breweries had been contacted by firms trying to sell wooden pallets; and six of the seven had been contacted by more than one firm. Although several breweries were completely satisfied with the pallets purchased through brokers, one brewery official said he did not want to use brokers because they sometimes sell substandard pallets. One of the two brewery officials that had not been contacted by pallet suppliers said, "We have to seek them out". He added that many firms do not want to sell to him because his brewery requires tupelo deckboards. One brewery said they had only one supplier for a short period of time, and they were striving to prevent such occurrences in the future.

Pallet needs varied seasonally for all the study breweries because of the seasonal nature of the brewery business. From 1960 through 1966 production of brewery products was highest in March through August, with peak production in either June or July. Most of the breweries try to spread pallet buying throughout the year, but the spring and summer months still are the period of greatest pallet demand.

Five of the nine study breweries said that they could not always get enough pallets when they needed them. The reasons given for this were that Department of Defense pallet demand increased significantly, and sometimes breweries did not give the suppliers enough production time. One brewery tried to improve their supply situation by helping to channel lumber to their pallet suppliers. Another brewery said that many of

their wooden pallet suppliers indicated they would be better able to meet demand if the pallet specifications were relaxed. Seven of the nine breweries said they were searching for new sources of pallets.

The breweries were generally satisfied with the quality of the wooden pallets they received. While all but one of the breweries replied that the pallets usually met their specifications, one brewery said that their original specifications had to be relaxed. And another brewery said that close examination was required to make sure the specifications were being adhered to. The brewery that replied that pallets generally did not meet specifications also said that the main shortcomings were thin deckboards and distorted wood grain.

Most of the breweries inspect pallets before accepting them. In some instances, inspection procedures are defined in the pallet specifications. A random sample is usually used as a basis for inspection; for example, one brewery uses a 10-percent sample. Inspection may be on a point basis, with certain points being given for improper dimensions, defective lumber quality, faulty nailing patterns, etc.; or inspection may be on a visual basis. One brewery uses pallet weight as a criterion for measuring moisture content.

Seven of the breweries said that the prices they were paying for wooden pallets were fair. One brewery official, who believed that prices were not fair, said that prices had increased almost 20 percent during the preceding year; and one official had no comment. Only two of the nine breweries said they would pay more for better pallets. One brewery official said he did not know whether he would pay more for better pallets until pallet-test results in the brewery were compiled. Another official, who would not pay more for better pallets, said the only components of the pallets his brewery was using that could be upgraded were blocks: he believed that center deckboards could possibly be downgraded without seriously affecting pallet quality.

It was impossible to specify the size of pallet inventories. However, an estimate based on industry-wide data indicates

that about 10.9 million pallet loads of brewery products were shipped by the study breweries (as opposed to 18.6 million pallet loads by all breweries in 1966. This estimate was based on these assumptions: (1) a typical pallet load consists of 155 gallons of packaged brewery products or 124 gallons of kegged products, (2) 90 percent of all packaged brewery products and 70 percent of all kegged products were shipped on pallets, and (3) 83 percent of all brewery products shipped were packaged and 17 percent were kegged.

Officials of six of the study breweries said they preferred more services from pallet suppliers such as storing and testing, and advising on repair techniques. Four of the six officials said that their suppliers gave such services. And three of these four said they had suppliers who would store pallets; one contract with a supplier said that 300 to 500 pallets would be available at all times. The other recipient accepted a service he did not request—a suggestion on how to repair pallets.

PALLET SPECIFICATIONS

Packaged Brewery Products

Pallets differed greatly among breweries in size, structural characteristics, species of wood allowed, moisture content limits, and nailing patterns (table 1 and fig. 3). The home offices of the nine study breweries had specifications for 10 pallets. These included: nine different sizes; eight block-type pallets; and two stringer-type pallets, one of which had notched stringers.

Some of the specifications called for blocks consisting of two pieces fastened together with corrugated fasteners, while others called for blocks consisting of only one piece. The strictest moisture content requirement was 18 percent for deckboards and 20 percent for blocks. Some of the specifications called for green deck supports (stringers or blocks) and seasoned deckboards; others called for all unseasoned parts. Only one brewery had a specification calling for preservative-treated pallets. The same specifications also called for blocks that had been dipped in clear paraffin.

Table 1.—*Characteristics of packaged beer pallets*

Brewery	Dimensions	Number and type of deck supports	Species allowed[2]				Allowable moisture content				Maximum weight
			Deckboards	Stringer boards	Block	Stringers	Deckboards	Stringer boards	Blocks	Stringers	
	Inches[1]						*Percent*	*Percent*	*Percent*	*Percent*	*Pounds*
1	32 x 37	9 block	All Group IV species except pecan	All Group IV species except pecan	Oak or gum	—	25	25	25	—	60
2	44 x 33	3 stringers	Tupelo	—	—	Group IV species	Not specified	—	—	Not specified	Not specified
3	32 x 38	3 notched stringers	Not specified	—	—	Not specified	Not specified	—	—	Not specified	Not specified
4	40 x 35	9 blocks	Group IV species	Group IV species	Group IV species	—	Not specified	Not specified	Not specified	—	35
5	38 x 33	9 blocks	NWPMA Group IV species	NWPMA Group IV species	NWPMA Group IV species	—	25	25	25	—	Not specified
6	40 x 32	9 blocks	Ash, aspen, basswood, or approved equal	Group IV species	Group IV species	—	Not specified	Not specified	Not specified	—	55
	32 x 40	9 blocks	Group IV species	Group IV species	Group IV species	—	Not specified	Not specified	Not specified	—	Not specified
7	37 x 32	9 blocks	NWPMA Group IV species	NWPMA Group IV species	NWPMA Group III species	—	25	25	25	—	52
8	44 x 36	9 blocks	NWPMA Group IV species	NWPMA Group IV species	NWPMA Group IV species	—	20	20	20	—	Not specified
9	37 x 32	9 blocks	Poplar	Gum or hardwood	Gum or hardwood	—	18	18	Unlimited	—	Not specified

[1] The first figure refers to pallet length and is the dimension perpendicular to deckboard length.

[2] Some specifications call for NWPMA (formerly National Wooden Pallet Manufacturers Association; now NWPCA — National Wooden Pallet and Container Association) Group IV species: white ash, beech, birch, rock elm, hackberry, hickory, hard maple, red and white oak, and pecan. NWPCA now uses a new species classification scheme, and the Class C species group for hardwood pallets is the same as the old Group IV species category. When a specification calls for only Group IV species, it is assumed that the specification refers to the classification scheme used by NWPCA. Other specifications call for NWPMA Group III species: black ash, pumpkin ash, white elm, red and black gum, soft maple, sycamore, and water tupelo. Species from the old Group I and III categories have been combined under the Class B species group for hardwood pallets in the new NWPCA species classification scheme.

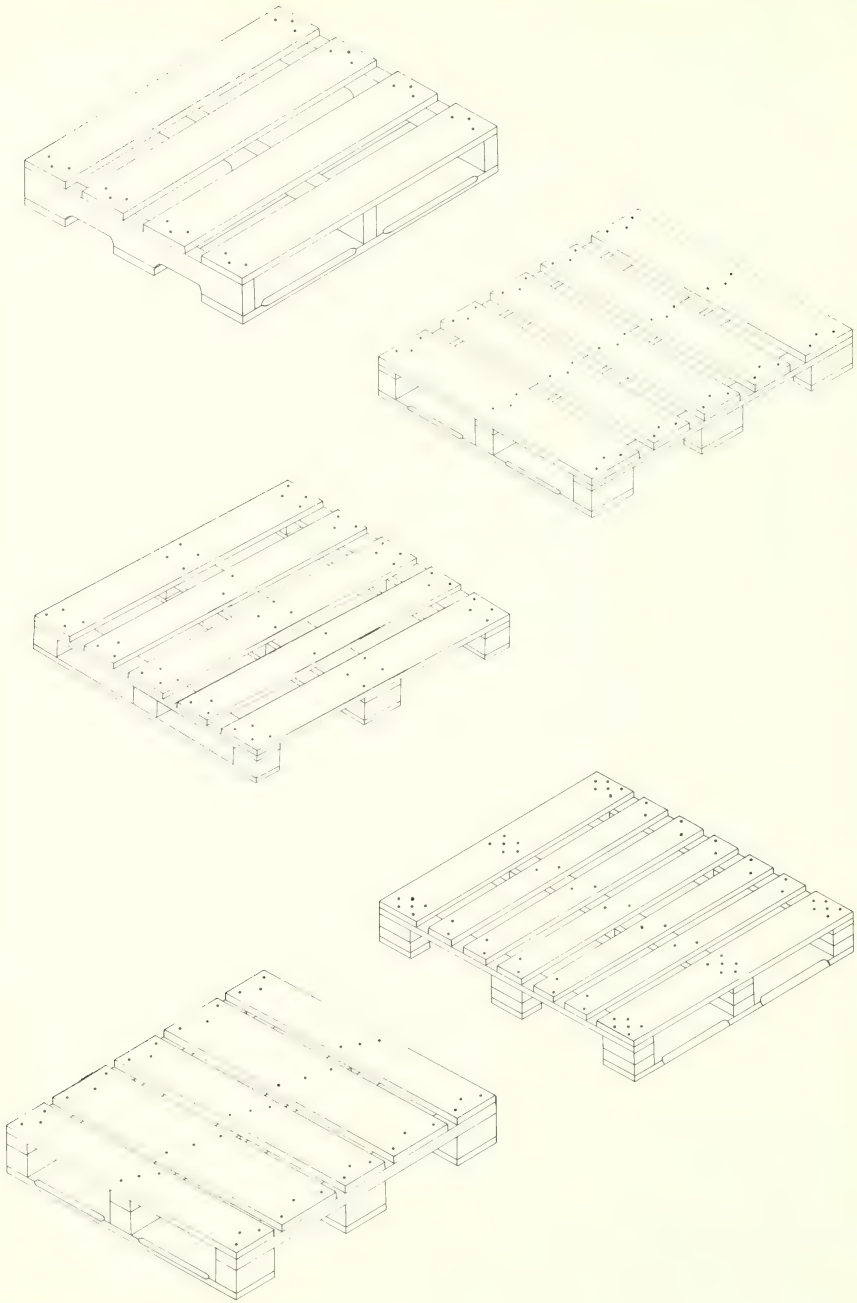


Figure 3.—Some of the different kinds of pallets used for packaged malt liquor.

The breweries have many different ways of specifying pallet nails. Some examples of nails to be used to fasten the bottom deckboards to stringers or blocks are:

- Two-inch long No. 11 gage drive screw or annular ring nails. The drive-screw nails require a minimum of four spiral flutes that have a helical angle of thread at the pitch diameter of 60° ± 5° with a plane perpendicular to the axis. The annular ring nails shall have 20 threads per inch running entirely around the nail.
- Drive screws (helically threaded nails) with 5/16-inch diameter head and diamond point, 6d Parkerized, 6 flute, 6.5 threads per 1 inch of nail.
- 2½-inch x 9/32-inch drive-screw nails.
- 3-inch cement-coated screw nails.
- 2½-inch diamond-point drive screws.
- 3-inch No. 10 resin-coated screw-shank nails or approved equal.

For identification, five of the breweries required the pallet manufacturers' name to be stamped on the pallet; four required the year and month of manufacture; and seven required the brewery's name.

Some of the specifications were vague; for example, "pallet grade" lumber was indicated in several instances. However, other specifications were explicit; for example:

> . . . "specifications are for wooden pallets which are to be used in automated machinery for loading the pallet, unloading the pallet and conveying the pallet on automated machinery, fork trucks and hand trucks, and not merely warehousing, consequently, are of a grade which provides pallets constructed to close tolerances, and good dimensional stability and required high quality material and workmanship. This specification recognizes that wood is by nature an unstable material under some conditions and the intent is to weigh the requirements of the highly stable automated machinery against the unstability of wood. Machining by nature has a limited tolerance and consequently requires wooden pallets to be of much higher grade than the normal warehousing pallet."

In addition to pallet variation among breweries, pallets varied considerably among plants of a particular brewery. Variation

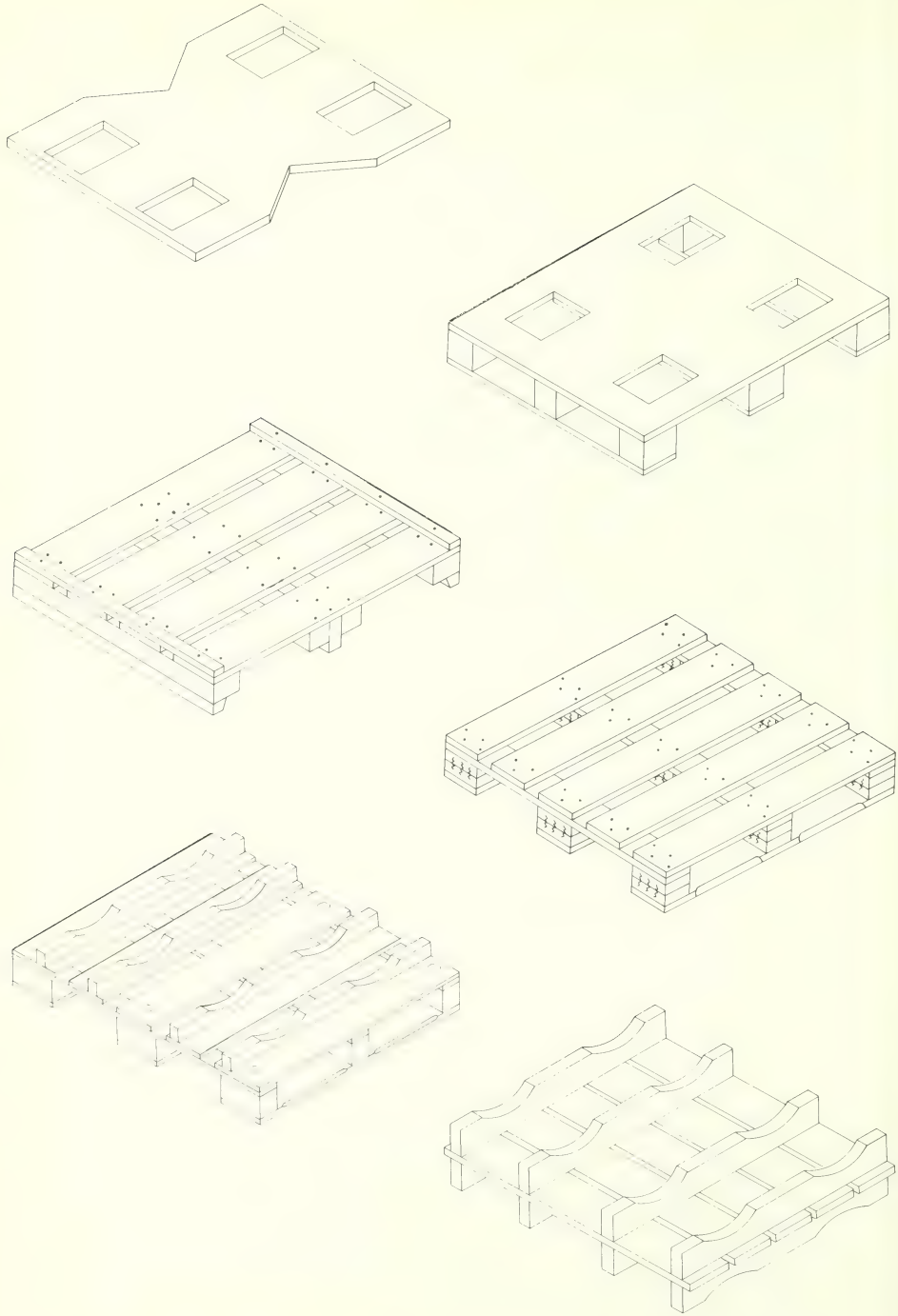


Figure 4.—Some of the different kinds of pallets used for kegged malt liquor.

among plants of a particular brewery may be caused by the following factors:

- Plants were often constructed or acquired at different times.
- Plants were sometimes acquired from another brewery that had equipment compatible with a particular kind of pallet.
- The method of transporting brewery products from plants to distributors varied considerably among plants.
- Transportation companies used a pallet that was similar to pallets being used by other firms in the same area.

Kegged Brewery Products

The main plants of six of the study breweries used pallets to move kegs, and the other three moved them manually. Two of the three breweries that did not use pallets for kegs in the main plant said they used them in other plants. The other brewery said they did not use pallets for kegs in any of their plants.

In most instances, species and moisture content descriptions for the keg-handling pallets were the same as or similar to descriptions for the package-handling pallets. Three of the breweries stacked kegs on lumber-base pallets; two of the breweries used lumber-base pallets in conjunction with lumber intermediate pallets (saddle pallets); and one brewery used plywood-base pallets in conjunction with plywood intermediate pallets (slip-boards) (fig. 4). The base-pallet specification called for "1-inch, C-D, plugged 1-side, exterior grade, rough-finish plywood," and the slip-board specification called for "1⅛-inch, C-C, plugged 2 sides, exterior grade plywood." Five different sizes for the six base pallets were used in the main plants: 44 x 33 inches, 44 x 36 inches, 40 x 40 inches, 32 x 40 inches, and 30½ x 34½ inches.

PALLET LIFE AND REPAIR

Only three breweries made estimates of pallet life in terms of number of moves. Two estimated that their pallets had a useful life of 20 round trips from brewery to distributor and return; the other gave an estimate of 100 round trips. Four breweries, who indicated they had no idea of pallet life in terms of trips,

made estimates of the useful life in years. These were 2 years, 3 years, 3¾ years, and 15 years. However, these yearly figures are essentially meaningless because the breweries could not estimate the average number of times a pallet is moved per year. One brewery said that some of their pallets were moved two or three times daily, while others were moved only once per month. The brewery that said that pallets had a useful life of 15 years estimated that they throw away about 6 percent of their pallets each year.

Four of the nine breweries said that damaged pallets were repaired in their plants. Three breweries indicated that they obtain repair parts from their pallet suppliers or lumber dealers. The other brewery maintains a stock of parts obtained from pallets that are damaged beyond repair. Most of the breweries have different criteria for deciding when a pallet is damaged beyond repair. One brewery considers a pallet to be damaged beyond repair when a stringer or inside block is broken.

The five breweries that do not repair damaged pallets in the brewing plant send them out to independent repair shops. These shops are generally located very close to the brewing plants. Most of the independent repair shops charge the brewery a standard rate for each pallet that is returned to the brewery. One brewery official said that about 85 percent of the pallets sent to an independent repair shop were returned.

One brewery utilizes its own repair facilities and an independent repair shop. If less than one-third of a pallet is damaged, it is repaired in the brewery; if more than one-third is damaged, it is sent to the independent repair shop if the estimated repair cost does not exceed a specified amount.

One brewery repairs about 40 percent of its pallets each year, compared with 60 percent several years ago. The reduction is a result of more mechanization and better handling practices, such as using blunt tips on the end of lift-truck forks.

For the breweries that sent pallets to independent repair shops, the repair cost ranged from $1.00 to $1.19 per pallet. And for the breweries that repaired pallets themselves, the estimated repair cost ranged from $1.19 to $1.25 per pallet. Several officials

of brewing plants that repaired pallets had no idea how much pallet repair was costing their brewery.

PALLET EXCHANGE

In the brewing industry there are few, if any, pallet-exchange programs. Because of the variation in size and design of pallets in use, the major obstacle to establishing an exchange program is deciding on a standard pallet. Most of the brewery officials said they would be reluctant to use a different kind of pallet because of the costs of changing handling equipment and warehouse layouts.

Some breweries have established limited pallet-exchange programs with firms that supply bottles, cans, labels, caps, and other materials. Other breweries buy the pallets and send them to their material suppliers.

The breweries mentioned several problems associated with the use of wooden pallets for malt liquor handling:

- It is difficult to get pallets back; sometimes railroad employees dump empty pallets out of rail cars.
- Discarding damaged pallets is a time-consuming process.
- Poorly manufactured or slightly damaged pallets sometimes jam automatic palletizers and depalletizers.
- Protruding nail heads damage packages.
- The bottom surfaces of some pallets are too smooth to allow proper movement on conveyors.

Unit Load Features

Generally, palletized unit loads consisting of cases of filled bottles or cans are stacked three pallet-loads high (fig. 5). Palletized unit loads consisting of cases of empty bottles or cans are stacked four pallet loads high.

Unit loads vary considerably in the same brewing plant as well as among breweries. For example, the unit loads in one brewery varied as follows:

- Weight range of a case of filled cans or bottles — 22 to 50 pounds.

Figure 5. — Stacking full cases of malt liquor in a warehouse.

PHOTO CREDIT: F. & M. SCHAEFER BREWING CO.

- Weight range of a case of empty returnable bottles — 14 to 25 pounds.
- Case length range — 14.25 to 19 inches (16 different lengths).
- Case width range — 9.38 to 12.75 inches (16 different widths).
- Case height range — 5.0 to 12.0 inches (14 different heights).
- Range of total number of cases on a pallet — 32 to 80.
- Weight range of a unit load of filled cans or bottles — 1,560 to 2,170 pounds.
- Height range of a unit load of filled cans or bottles — 52 to 58 inches.

This same brewery had 19 different case sizes and 9 different stacking patterns. Since this example shows only the variation in one plant, it becomes easy to understand the magnitude of unit load variations among breweries.

Methods of stacking kegs on pallets are also variable. When lumber base pallets are used in conjunction with lumber intermediate pallets, a unit load commonly is three kegs high (fig. 6) When the kegs are full, such a load weighs about 2,100 pounds.

Distribution

The distance brewery products are shipped from the plant varies considerably and depends on factors such as number of plants operated by the brewery and plant location. The maximum shipping distances within the continental U. S. for the main offices of the 9 study breweries ranged from 180 to 3,000 miles.

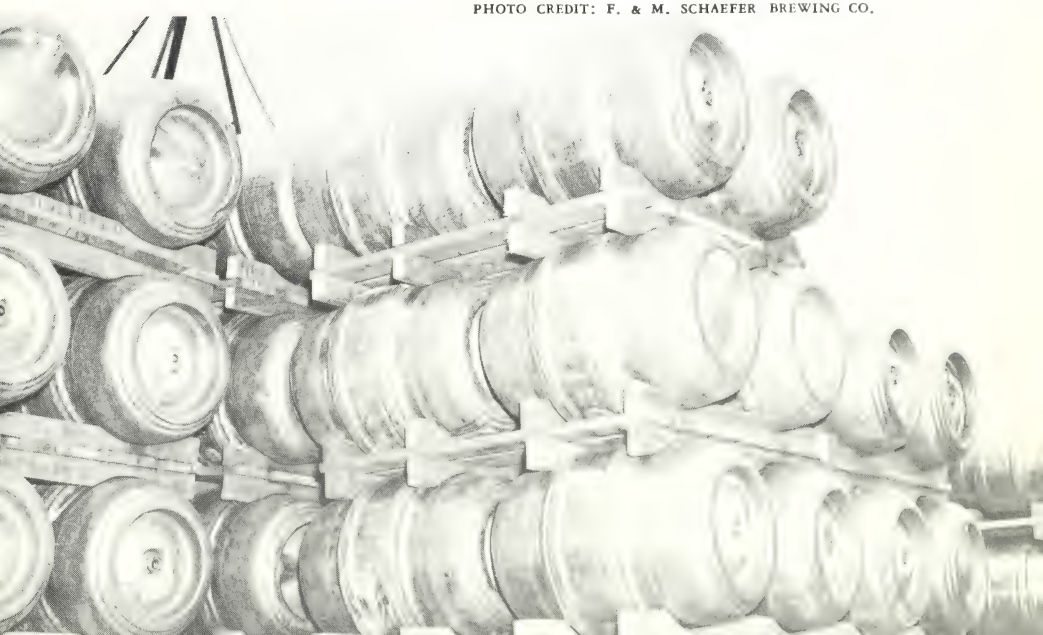
The method of transportation also varied considerably among the main plants of the study breweries. For example, the range of shipments of brewery products by rail car was 0 to 67 percent; and 42 to 51 pallet loads commonly were shipped in a 50-foot rail car.

Several breweries said they tried to ship as much as possible by truck because truck-return rates for empty pallets were more economical than railroad-return rates. One brewery was able to get lower railroad-return rates by showing the railroad that damage claims are reduced when pallets are used.

Most brewery products were shipped from the breweries to the warehouses of distributors who handle only malt liquor. However, a small percentage was distributed near the plants by brewery route trucks or was sent directly to food warehouses.

Figure 6.—Unit loads of kegged malt liquor.

PHOTO CREDIT: F. & M. SCHAEFER BREWING CO.



A majority of the distributors serving the study breweries were equipped to handle palletized loads:

Brewery	*Proportion of distributors equipped to handle palletized loads (percent)*	*Proportion of volume handled by these distributors (percent)*
1	90	85-90
2	75	95
3	100	100
4	70-80	70-80
5	95	95
6	95	98
7	([1])	([1])
8	98	98
9	50	60-65

[1] Majority.

However, great inefficiencies will exist in the distribution process until those distributors who cannot handle palletized loads add the necessary equipment.

All but one brewery official said he believed that distributors handle brewery pallets carefully. The official who did not believe pallets were handled carefully said they were treated roughest in the Southeast. A main complaint was that the distributors often store pallets outdoors. Another complaint was that some pallets were damaged by distributors' employees who pulled the pallets out of the trucks by chain.

Only one official gave an estimate of the percentage of his brewer's pallets lost or damaged beyond repair by distributors—3 percent. Seven of the nine breweries charged distributors a deposit of $2 to $3 per pallet. However. the breweries said it is often difficult to enforce and collect the deposit.

A LOOK AHEAD

The brewing industry should provide a large and growing wooden pallet market for many years because of: (1) population growth and increased per-capita brewery products consumption (during 1962-66 total brewery products consumption increased 15 percent and per-capita consumption increased 9 percent), (2) the current high degree of dependence on a unit-load

handling system utilizing wooden pallets, and (3) expectations that a large volume of brewery products now being handled manually will be handled by unit-load on wooden pallets in the near future. All but one of the study breweries have considered adopting non-wooden pallets or a non-palletized materials-handling system. Aluminum, steel, and plastic pallets were usually rejected because the cost per trip would be unjustifiable.

Some specific shortcomings of aluminum pallets were: (1) they broke too easily and could not be repaired; (2) they required cleaning; and (3) many of them were stolen. Some breweries experimented with disposable pallets, but officials in these plants said they believed these pallets cost too much. Slipsheet and clamp handling were found to be unsatisfactory because the distributors would have to unload packages manually. Specific objections to clamp handling were: (1) clamps damaged the packages; and (2) because of the non-standard dimensions of some packages, they could not be stacked so they could be moved readily with a clamp truck.

LITERATURE CITED

Carlson, Tony C.
1966. The Market for Wood Pallets in the Steel Industry. U. S. Dep. Agr. Forest Serv. Res. Paper NE-53, 15 pp., illus. NE. Forest Exp. Sta., Upper Darby, Pa.

Crivella, B. J.
1965. Malt Liquors. *In* U. S. Industrial Outlook: 1966. U. S. Dep. Com., Business and Defense Serv. Admin. Rep., 213 pp., illus.

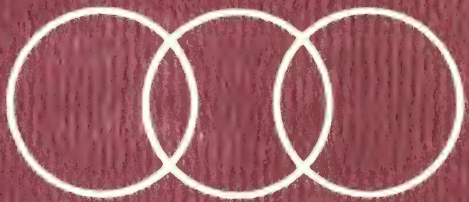
Sanchagrin, T.
1968. The Beer Brawl. Marketing/Communications 296 (1): 27-30, 32, illus.

United States Brewers Association, Inc.
1967. The Brewing Industry in the United States. Brewers Almanac, 127 pp., illus.

THE FOREST SERVICE of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

Guidelines for Establishing

FORESTRY COOPERATIVES



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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

IN COOPERATION WITH
FARMER COOPERATIVE SERVICE, U. S. DEPARTMENT OF AGRICULTURE

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IF YOU are thinking about starting a forestry cooperative, the best advice anyone could give you is: before taking any action, consider all the benefits and advantages, and then consider all the pitfalls and problems.

Certainly cooperative action has many advantages; and many cooperative businesses have enjoyed great success. But most of the forestry cooperatives tried in the United States have failed as businesses.

Of the 68 forestry cooperatives started in the United States in the last 50 years, 47 are no longer operating. Why didn't more of them succeed? Most of the cooperatives established before 1961 went out of business for one or more of the following reasons: insufficient interest and support by members, inadequate capital, lack of a sufficient volume of business, or inadequate management.

Still we believe that there is a place for the forestry cooperative in our economy. And an increasing interest has been shown in the cooperative business structure as a means for developing better timberland management and more efficiency in marketing forestry products. This interest is evidenced by the organization of 11 forest-based cooperatives since 1961, the establishment of an interagency committee by the U. S. Department of Agriculture to assist in developing forestry cooperatives, and the development of forestry cooperative advisory groups in most states as part of the Rural Areas Development program.

The Forest Products Marketing Laboratory of the U.S.D.A. Forest Service's Northeastern Forest Experiment Station has been studying the history of the forestry cooperative, and has analyzed the experiences of the cooperatives that have failed as well as those that have succeeded. In addition, the New Services Division of the U.S.D.A. Farmer Cooperative Service has a continuous program of research to assist members and managers of cooperatives. Out of these studies we can offer some practical guidelines to any group that is thinking about starting a forestry cooperative. Here are the highlights:

WHAT IS A COOPERATIVE?

Understand how cooperatives differ from other forms of business organization. Know the advantages of group action, but understand that organizing on a cooperative basis cannot by itself guarantee success.

PEOPLE INTERESTED?

Identify the origin and nature of the interest, and the motivations of the people interested. If interest is lacking, postpone action till interest is expressed.

COMMUNITY ATTITUDES?

Determine how the community might react toward a new cooperative, or to other forms of business organizations.

ECONOMIC JUSTIFICATION

Conditions favor a cooperative only when existing commercial facilities or services are inadequate, costs for services are too high, or prices received by woodland owners or timber processors are too low. If a competitive situation exists, the justification for a cooperative must be strictly economic.

TYPE OF COOPERATIVE?

Determine the type of forestry cooperative needed in light of the expressed interest, the services needed, the available volume of business, and the markets to be served. For the type selected, outline the activities or services to be performed.

RAW MATERIAL SUPPLY?

Inventory the present and prospective timber resource and its commercial availability within the proposed cooperative's operating territory. Determine whether the resource will sustain management, processing, or marketing activities under the limiting conditions.

PARTICIPATION?

Find out who will support a cooperative before — not after — organizing, and the extent to which prospective members will participate in its affairs. Identify the communication difficulties likely to be encountered between management and members, and devise methods for avoiding or overcoming these barriers.

MARKETS?

Inventory the number and characteristics of potential market outlets within the operating range. For each market outlet, determine its normal volume requirements that would affect the plan of operation. Decide how the cooperative can best serve its market outlets while adequately serving members' needs.

FINANCING?

Determine the amount of capital required for initial investment, working capital, and expansion; and ascertain the amount of capital that can be obtained from all sources. Members should provide a substantial portion of the total capital requirements. Design a financial structure that is conservative but flexible and growth-oriented.

LABOR AND MANAGEMENT

Determine the availability of labor with the needed skills. Develop a training program where needed skills are lacking. Identify the qualifications required of a manager. Decide whether operations should begin with a part-time manager.

ORGANIZATIONAL CONSIDERATIONS

Use whatever assistance is available from both private and public organizations. Seek legal counsel in formulating the cooperative's organizational structure and business documents.

WHAT IS A COOPERATIVE?

The prospective members and organizers of a cooperative ought to understand fully how this type of organization differs from other forms of business organization. They should realize both the major advantages and the limitations of group action.

A cooperative is a business organization of member-patrons who work together for mutual benefit in marketing products, purchasing supplies, or obtaining services at cost.

A member of a cooperative serves a dual role as patron and owner. As patron, he is responsible for actively supporting his organization. As owner, he is responsible for participating in the affairs of the organization. Hence, as owner-patrons, members share responsibility for the success or failure of their cooperative.

Unlike the general business corporation, savings above the cost of doing business are returned to patrons in proportion to their use of the cooperative rather than in proportion to their dollar investment. Some cooperatives do pay moderate dividends before paying patronage refunds, but such stock dividends are ordinarily limited by their bylaws to 6 percent or less.

Democratic control is another characteristic that distinguishes a cooperative from the general business corporation.

In an investor-oriented corporation, where the objective is to maximize returns on invested capital, voting is on a stock basis. In a cooperative, voting is on the basis of one-member, one-vote; or on the basis of the amount of business the individual contributes, regardless of the amount of stock he holds. The primary objective of a cooperative is to render services at cost.

If invested capital were the basis of control in a cooperative, a few members with large investments could outvote a majority who might be the major patrons. They could decide the services to be rendered and vote for large dividends. Hence the very purpose of a cooperative effort—to provide needed services at cost—would be defeated.

BENEFITS OF GROUP ACTION

Group action enables member-patrons to solve problems, obtain or provide services, and gain efficiencies they often cannot attain through individual action (fig. 1). For example:

A group arrangement can help woodland owners to operate small tracts of merchantable timber scattered over wide geographic areas, thus permitting them to cut on a commercial basis. As a result, timber stands in an area can be given better care and management.

Marketing timber of comparable species, grade, and size as one lot, rather than as several lots sold individually, enables growers and processors to better serve buyers' needs.

By consolidating the money they are able to pay for management, woodland owners and processors are in a better position to pay salaries needed to attract and keep capable managers. They can also better afford to hire woods personnel needed for efficient operations.

By pooling finances, producers can afford to purchase specialized expensive equipment such as large tractors, transport vehicles, debarking machines, and similar equipment needed for large-volume operations. By pooling orders for supplies and

Figure 1. — In areas like this farmland, where timber stands are small and scattered, there is economic justification for a forestry cooperative association. Through cooperative action a group of small owners can get management and marketing services that as individuals they could not afford.

equipment, forest owners and processors can obtain discounts for quantity purchases and can also reduce costs of transportation. And, by incorporating as a cooperative, member-patrons can increase the possibility of obtaining financial assistance from both public and private sources.

This list of advantages associated with group effort is by no means complete. It merely suggests some advantages group efforts offer over individual operations.

A forestry cooperative must be organized so as to capitalize on existing conditions. Since conditions vary from area to area and in individual circumstances, no set procedure can be recommended that applies to the formation of all types of cooperatives. However, certain guidelines can be set forth that will be helpful when considering any type of cooperative activity as a means for developing better forest-land management, timber processing,

and marketing. Appropriate modifications can be made in the criteria to suit prevailing conditions.

Interested People

The first consideration should be the origin and nature of interest in developing a cooperative. Does this interest stem from within the area under consideration, or from an outside source? What are the motivations of those expressing interest? Are these persons business leaders, innovators, or followers? If initial interest in a cooperative does not originate from local sources, can a substantial and sustained interest be developed? Answers to these questions may serve as a basis for deciding whether to proceed with a feasibility study.

Interest can stem from many sources: woodland owners, primary processors, other manufacturers that rely on the products to be handled, or others interested in developing improved woodland management and marketing. The degree of local interest developed is especially important. Most of the recently organized forestry cooperatives held off making capital investments until a minimum number of prospective members signed preorganizational contracts or purchased stock.

The presence of interested local producers—particularly community leaders—who will take an active part in the organizational effort and subsequent operations of a new cooperative often means its success. If such people are not interested, it may be advisable to postpone organizational work until they do become interested.

Closely identifying the interest is also important because it partially determines the form of business organization that might be established. If the organization is to be owned and controlled by woodland owners, it can be incorporated as a bona fide agricultural cooperative. The business might then be eligible for loans from the district banks for cooperatives of the Farm Credit System.

If the organization is to be owned and controlled by other than woodland owners, the group could incorporate to perform certain services as a cooperative association but would not qualify for loans from the banks for cooperatives. In contrast to a regu-

lar corporation, however, such an association might qualify for certain exemptions under the Internal Revenue Code.

If those expressing interest are members of an existing cooperative, or have had previous satisfactory experience with such an organization, they are more likely to participate in a new cooperative effort. On the other hand, if prospective members lack cooperative experience, or have had unsatisfactory experiences, they are apt to be less enthusiastic about participating.

An absence of interest within a proposed survey area may be due to a lack of knowledge about the cooperative business structure and potential benefits of group action, or a lack of communication among resident woodland owners and nonresident owners. And some who have latent interest in forming a cooperative may be persuaded by subtle pressures or other means to preserve the status quo. There may be dissension, factionalism, and unusually harsh competition—especially among small processors—promoted by vested interests that would either prejudice or prevent constructive communication. Cooperative action may have been discussed and deemed unworkable, or there may be a lack of leadership in the area.

If local interest is lacking, but there appears to be a need for some type of forestry cooperative, educational work may have to be done. Both present and projected interest resulting from an educational program should therefore be considered essential parts of a feasibility study.

Community Attitudes

The attitudes and reactions of business people and others in the community toward cooperatives can help or hinder a new cooperative's activities. Although neither a negative nor passive attitude will necessarily prevent the cooperative from carrying out its objectives, a favorable community reaction toward the organization will help increase its acceptance among potential members and will make operations easier. Accordingly, community attitudes and expected reactions toward the proposed cooperative should be ascertained. And the possibility of changing or modifying community attitudes should also be taken into consideration.

Economic Justification

If there is enough interest in forming a cooperative, then the organizers must decide on the economic justification for the business. Is the purpose of the cooperative to satisfy an economic need? Or is the purpose to satisfy a noneconomic need such as: (1) a social welfare program to provide employment, vocational training, or similar activities without regard to economics of the program; (2) an experiment or pilot project to test a hypothesis; (3) a program contrived to promote an idea; or (4) a program to enhance the aesthetic, nonprofit recreation values of an area?

Distinguishing between an economic and noneconomic justification is important because: (1) the organization's purpose, functions, and goals can be more clearly defined; (2) the particular need or combination of needs will affect all decisions and activities of the organization; (3) the degree of success of the enterprise can be predicted within certain limits by realistically determining the needs to be satisfied and the economic resources available such as land, labor, capital, and management; and (4) making the distinction helps to determine if subsidization is justified, if a certain amount of capital can be generated for investment, or both.

In a competitive market, justification for a new business organization must be strictly economic if it is to survive without direct or indirect subsidies. Such subsidies may take the form of grants or unusually low-interest loans, preferred treatment or protection in the market place, free administrative or technical assistance, or special treatment with regard to purchasing publicly owned timber.

The purpose of a cooperative is not to eliminate marketing functions or services, but rather to consolidate these activities for more efficient operation or to provide services not available from existing outlets. If the group operating through a centralized unit cannot operate at least as efficiently as an alternative economic system, there is no economic justification for the organization. If it operates more efficiently, the results will be evident

in terms of increased monetary returns, improved services, or both, to individual members.

The effect on existing businesses resulting from establishing a new cooperative should be considered. Often the point is made that a new business should not duplicate existing services within the marketing area. Except for publicly regulated utilities, monopolies are not usually considered to be in the best interest of the consumer nor inherently efficient. If efficiency of distribution can be improved—even at the cost of substituting one system for another — perhaps a change should be made. Landowners and consumers need not subsidize an inefficient operation or system if there is an alternative that will not require subsidization.

Some criteria for objectively evaluating the economic justification for a cooperative are:

- Will the business provide new activities or services not available from the present production or marketing system? If so, there is need to estimate the probable demand for these activities and the probable cost or benefit. Unless a new activity will result in greater returns to patrons in the long run, it should not be undertaken.

- Can the new cooperative perform the same activities and provide the same services as the present or alternative system, with equal or better efficiency, at equal or less total average cost? Operating at equal costs may not improve economic efficiency, but landowners may wish to vertically integrate their production and marketing processes — even though their cooperative's efficiency is no greater than that of the present system — if it enables them to employ idle land, labor, management, and capital resources. Integration also enables them to maintain control over their product further along the channels of distribution.

- If the present marketing system is considered inadequate, unfair, or inefficient, will the new cooperative bring members' returns up to or above competitive market prices prevailing for similar products produced under comparable conditions and sold in other markets?

If market outlets do not exist, the reasons should be determined. This situation may prevail because of: (1) fragmented forest acreages that are uneconomical to harvest; (2) an insufficient volume of merchantable species or inadequate quality of timber; (3) a significant amount of the timber resource unavailable for commercial use; (4) inaccessibility of timberlands; (5) insufficient knowledge of the profit potential from the forest resource; or (6) other barriers to profitable investment in the area's wood industry.

If market outlets exist, private capital investment will generally flow into an area if an adequate return can be realized. If the area's timber resources and production potential have not previously attracted private capital, one should consider whether it is reasonable to expect a business capitalized from any source to survive without subsidization.

Type of Cooperative

Once the economic justification for starting a forestry cooperative has been determined, it then becomes necessary to outline the specific types of activities to be performed by the cooperative and the type of organization necessary.

Some of the activities that might be considered are: (1) woodland management services; (2) marketing services; (3) combined management and marketing services; (4) custom processing activities; (5) processing and marketing activities and services; (6) management, processing, and marketing services; and (7) an integrated operation providing management, processing, secondary reprocessing for specific business users, manufacturing, and wholesale marketing. The following types of cooperatives, classified according to the major function performed, might be developed to provide one or more of these services:

Management cooperative.—Services provided in this category could range from timber cruising and developing forest management recommendations to providing complete management services under a long-term contract (fig. 2). Services might include one or more of these activities: surveying, cruising, and developing either limited or comprehensive management plans; supervising production and maintenance programs; and, harvesting and

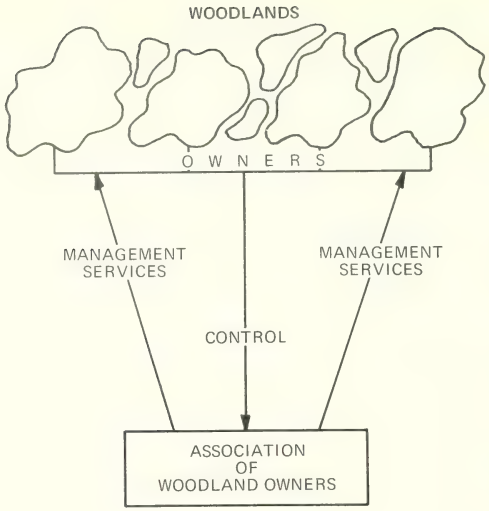

Figure 2.—Diagram of a limited management cooperative. Woodland owners combine their resources, support and control their association, and in return receive management services at a lower cost than they could as individuals.

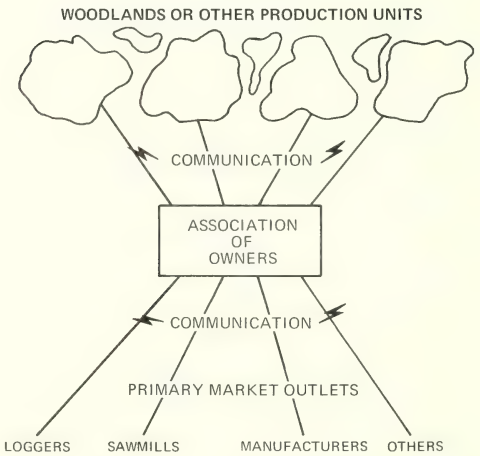

Figure 3.—Diagram of a limited marketing cooperative. This provides a line of communication between sellers and buyers on a fee basis. Woodland owners form an association to provide information on market conditions: to members about markets; to buyers about supplies available.

selling timber. When considering what management services are needed, you should make a thorough analysis of what services are already available through state and private forestry programs and consulting foresters.

Marketing cooperative.—Services in this type of cooperative

can range from simply providing a line of communication between buyers and sellers to determining cutting practices, marking, harvesting, concentrating and storing, standardizing and grading, selling and transporting, collecting payments, and dispersing returns (fig. 3 and fig. 4).

Management-marketing cooperative.—If both management and marketing services are needed, the specific type and combination of activities and the proportion of investment devoted to each segment should be considered, and their comparable values should be analyzed and tentatively determined (fig. 5).

Custom processing cooperative.—Processing activities such as sawmilling, yard-seasoning, kiln-drying, planing, or more refined processing can be performed for members, local users, or larger

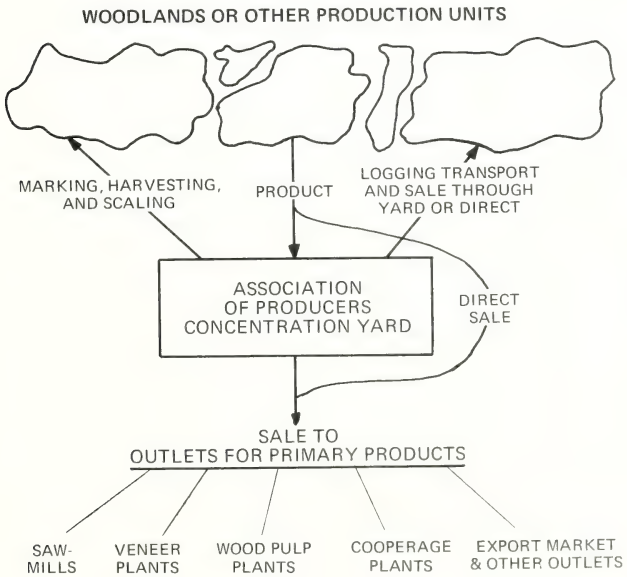

Figure 4.—Diagram of an integrated marketing cooperative. This provides all activities under contract from marking timber to collecting payments from buyers and making repayments to members. Area of operation is limited by transport for an individual concentration yard and by management requirements for a federation of yards.

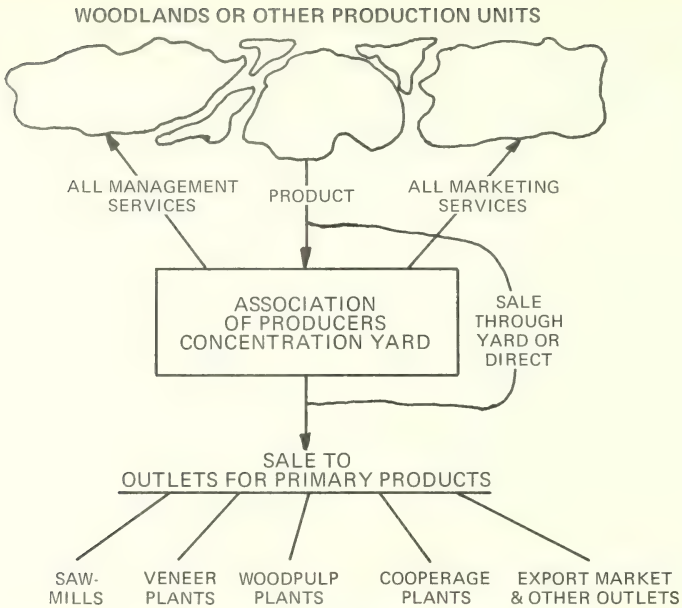

Figure 5. — Diagram of an integrated management-marketing cooperative. This provides complete woodland management, marketing, and related services to members under long-term agreement for producing and distributing primary products.

and more diversified market outlets. For example, this type of cooperative could supply the demands of a federation of agricultural cooperatives.

Processing-marketing cooperative.—This type of activity could vary from a unit providing processing and marketing activities for woodland owners to that of assembling products from several processing plants (either physically, by title, or by contract) under a central marketing agency. Such an association could provide a specialized and possibly more efficient method of sale and distribution.

Management-processing-marketing cooperative.—Various combinations of this type of organization could be developed. A typical operation would involve the integration of woodland management services with processing and marketing activities. The type and kind of services and activities to be performed, the

degree to which they are to be carried, and the resources required for each segment of the operation must be determined. Here again, comparable efficiencies of alternative systems will be of first importance in estimating the organization's overall feasibility.

Industrial complex. — An industrial complex could be a complete vertically integrated operation. It might involve timberland management and harvesting, processing, manufacturing, and selling wood products to users or retail market outlets. Management could be provided by a central unit, or each process could be maintained autonomously and be federated as a central coordinating unit.

Raw Material Supply

The timber resource, its location, availability, and proximity to markets will have the utmost importance on the types of service to be performed by a forestry cooperative.

Lack of an adequate volume of timber was a major cause for the discontinuance of several forest-product cooperatives. This was often due to an insufficient knowledge of the availability of timber, inadequate supply of the desired species and quality, and lack of a steady supply of raw products.

A suggested procedure to help avoid such operating problems is as follows:

1. Inventory the timber resources in the area under consideration by volume, species, size, quality, size of tract, ownership, and residence of owner. This information may be available from forest-survey data or can be obtained from a more concentrated resurvey (fig. 6).
2. Determine the timber-resource potential to supply various types of outlets such as the sawlog, veneer, pulpwood, plywood, tie, pole, and piling industries.
3. Estimate the growth rate and project future volumes of timber available by species, size, and quality under various management conditions. (Some examples are: no management, limited management services and sustained-yield cutting, or full management services and sustained-yield cutting by the cooperative.)

Figure 6.—Taking inventory in a woodlot. Close inventory control is important for success of a forestry cooperative.

4. Estimate the potential annual timber drain from the resource area for periods up to 50 years. A good estimate will provide important guidelines for making operational decisions and planning the cooperative's growth and development.
5. Assuming different degrees of participation by prospective members, determine the minimum combination of timber volume, species, size, and quality by size of tract and transporting distance that will allow the cooperative a reasonable degree of success.
6. Assuming that a need exists and that total participation by prospective members can be expected, determine whether present and potential timber resources will sustain either management, marketing, or processing cooperatives under differing conditions.

Membership and Participation

An adequate volume of timber within a marketing circle will be of little value to a proposed cooperative unless the cooperative can enlist enough members who will participate actively in its activities. Lack of members, diminishing interest, and not

enough active participation were the major causes of failure for some forestry cooperatives.

Consider fully the potential membership for the three main types of cooperatives: (1) *Landowner cooperatives.*—Members may include owners or operators of all privately owned woodland tracts. In addition, municipal tracts as well as timber tracts owned, leased, or administered by trusts, holding companies, and wood-using industries are potential members of this type of cooperative and should not be overlooked. (2) *Primary product producers' cooperatives.* — Members may include landowners, loggers, sawlog dealers, and producers of pulpwood, Christmas trees, maple syrup, and other primary products or byproducts. (3) *Secondary product producers' cooperatives.*—Members may include sawmill operators, planing mills, pallet manufacturers, and other manufacturers of secondary wood products.

Founders of a new forestry cooperative should be careful not to overestimate how many members they can enlist, or how much participation they can expect from their members. The history of forestry cooperatives reveals a serious misconception about the motivations, attitudes, desires, and needs of possible members. Too often the expectations of membership and active participation have been overestimated, and the cooperatives that did this never accomplished their goals.

What's in it for me? will be the first question from prospective members. Benefits of increased prices or reduced costs will be the dominant factors affecting an individual's decision about whether or not to participate. The cooperative's capability to increase the potential member's net income will, within limits, determine his initial interest and will influence his subsequent participation. Yet in every area some landowners and operators will not participate because: (1) they do not wish to relinquish any control over their property; (2) they may not wish to disturb their woodlands for aesthetic, sentimental, or philosophical reasons; or (3) they may not be legally free to sell the forest products from their land because of indefinite authority, encumbered title, lease, agreements, and other legal or administrative reasons.

It is necessary to determine what can be expected from members in terms of: (1) accepting and carrying out recommendations of the cooperative; (2) accepting and honoring long-term contracts; (3) renewing contracts — especially short-term contracts; (4) honoring management and marketing agreements; (5) pledging land as collateral for borrowing capital for the cooperative; (6) performing harvesting and logging activities; (7) making substantial investments in the cooperative; (8) supplying timber on a scheduled or continuous basis; and (9) actively particpating in the cooperative's business affairs. Unfavorable response from the membership to these factors was especially troublesome to many past forestry cooperatives.

Past experience has shown that, in addition to an objective presentation of the facts, more scientific techniques are required to obtain realistic estimates of participation in a proposed cooperative venture for the years ahead. For this, the knowledge and experience of universities and other research institutions whose personnel are likely to maintain impersonal and objective attitudes should be utilized. Many schools, including the land-grant colleges, have developed and adopted reliable techniques for determining interest and projecting participation in various types of agricultural programs.

Most important of all for keeping members interested and participating is good communication between the cooperative and its members. Members must be kept informed about what the cooperative is doing.

Except for Christmas trees, maple syrup, naval stores, and a few other products, most forest tracts are not cropped annually. There may be a 5- to 20-year interval between the harvests of pulpwood and sawlogs. If management services are not performed for woodland owners, contact between the members and management will be infrequent unless steps are taken to maintain a line of communication. Many problems and misunderstandings arise from this lack of contact. To minimize this, many cooperatives maintain contact by correspondence, newsletters, personal visits, and other means such as assigning all members to a committee to keep them interested and informed.

Another factor that has to be considered is whether those having authority over the land are residents or nonresidents. If, as in the past, there is a continuous outgoing of owners, the business can probably operate with a membership comprised predominately of nonresidents. However, the association's success will depend to a large measure upon the degree of control exercised, the type of services offered and contracted for, the length of the contract period, and the cooperative's ability to communicate with the landowner.

Markets

As in any business, it is necessary for organizers of forest-land cooperatives to know as much as possible about markets for their products. Any cooperative should know at all times the exact number and type of potential outlets within shipping distance.

The importance of this knowledge is obvious when selling rough forest products. The number, type, and product diversi-

Figure 7. — Operators of a cooperative must know the markets for their products. This sawmill is making use of two markets by producing both lumber and cants.

fication of markets within shipping distance play important roles in determining whether sales should be made on a stumpage basis or through a concentration and sorting yard, and whether logging and transporting will become a necessary function of the cooperative (fig. 7).

Knowledge of the number and type of outlets for any given product will be important to the cooperative, especially if one of its objectives is to develop increased bargaining power. The bargaining power of a seller is more easily increased when selling to a number of competitive buyers rather than to a single buyer or to a very few noncompetitive outlets.

There are several other pertinent factors about market outlets that should be considered:

1. For each outlet, determine its business characteristics by type of product, size and normal volume of purchase, buying and selling policies, and other internal business factors that would affect the cooperative's activities and plan of operation.
2. Estimate the degree of competition between market outlets, especially among buyers who purchase similar timber products. This knowledge will be helpful when deciding whether sales should be made by auction, bid, or negotiation. It may be even more significant when determining the cutting program and specific sales practices to be employed.
3. Determine whether each market outlet owns or otherwise controls raw material resources that might be competitive with the cooperative's products. If they do, such a situation would be of particular significance to a cooperative's bargaining position—especially when the buyer is both large and isolated.
4. Calculate the new cooperative's benefit to the respective market outlets. If the cooperative can justify its activities on the basis of decreasing the buyer's product costs, increasing the quality of products he receives, or efficiently providing other worthwhile services, its acceptance within the market will be reasonably assured.
5. Ascertain whether the cooperative's activities will supplement, complement, or compete with the programs of the respective

market outlets. If the activities are either supplementary or complementary, the new cooperative will probably find its business associates to be much more receptive than if they were competitive.

6. Estimate the degree of receptivity and cooperation from the market, both as a marketing system and as individual businesses. The cooperative's ability to provide a useful service for the market outlets will basically determine whether the outlets will be passive, nonreceptive, or receptive.

Financing

Most forest-based cooperatives in the United States experienced serious financial problems from the very beginning. Three of the major problems encountered were: (1) lack of adequate capital during the initial stages of development; (2) inadequate financial structure to provide working capital for both an efficient current operation and for expansion; and (3) overborrowing and overcapitalization to the extent that overhead costs could not be met from sales margins. Although insufficient capital was rarely considered the most direct cause of failure, it significantly contributed to operating problems and often reduced or even prohibited growth and development. Too often, organizing groups failed to determine the true financial needs, and failed to set up a financial structure to meet these needs.

The amount of capital needed for initial investment, working capital, and growth will depend upon many factors and can be estimated only for a given circumstance. Important among these factors are the type of association to be established, physical plant requirements, activities to be performed, and planned operating methods. Minimum requirements can be estimated as follows:

A minimum-size (one-employee) management-service cooperative would need a capital investment of $12,000 to $15,000 for the first year of operation. A one-man timber-marketing cooperative would require approximately the same capital investment. And a limited management-marketing cooperative might require a minimum investment of $20,000 to $25,000 for the first year of operation.

The fixed capital investment required for an efficient sawlog processing-marketing cooperative would range from $150,000 to $250,000 for a one-shift operation. The financial requirements for an industrial complex would be difficult to project. For example, those for a proposed eastern Kentucky complex were estimated to be more than $4,000,000.[1]

Is the capital available? Organizers of cooperatives should determine whether the required capital can be obtained from members through one or more of these methods: membership fees, sale of common and preferred stock, retained earnings, borrowing on members' timber resources as collateral, or borrowing on warehouse receipts.

Perhaps a judicious combination of the above-mentioned methods of financing is advisable. The more members invest in their organization, the more likely they are to take an active interest in the operation and to support the organization with their patronage.

Most forest cooperatives have not relied on membership fees, sale of common and preferred stock, or loans secured by members' timber for their initial capitalization. Most cooperatives have kept the initial fees and capital investment at a minimum in order to attract as many members as possible. To some degree, this practice caused a multitude of later operational problems. Primarily because of insufficient working capital during the early stages of operation, most cooperatives had difficulty providing enough services to maintain member interest and participation and to stimulate additional investment.

Except for one stock corporation that charges only a $10 membership fee, the more recently organized forest cooperatives —especially those marketing annual crops—have required substantial investments of their members. In general, they obtained a large part of their capital by selling both common and preferred stock to members in proportion to their gross volume of business before joining the cooperative.

For example, three recently organized marketing cooperatives

[1] U. S. Department of Commerce. A Forest Industry Processing and Marketing Complex for Eastern Kentucky. 144 pp., illus. 1963.

obtained their basic operating capital from: (1) annual assessments on the member's total gross sales, including both the sale of products made through the cooperative and those made to all other buyers; and (2) by charging a small commission for products sold annually through the cooperative. This means that members who sold products through the cooperative were assessed twice for the same product. The reason is that the type of services provided by the cooperative such as advertising, quality control, grading rules, and promotion, was helpful to all member-producers regardless of whether or not they sold most of their products through the cooperative. The commission charged on sales through the cooperative was designed to equalize the cooperative's cost of service in proportion to benefit received. Patrons received an extra service and therefore should pay more.

Another question that often arises is whether nonvoting stock or certificates of investment should be sold to nonmembers. Members may not be able to meet the investment required for total capitalization. So other sources of funds must be considered.

One method of fund-raising often used is the sale of limited-interest, nonvoting, preferred stock to individuals outside the cooperative membership. This practice incurs no particular disadvantages if preferred stock sales are based on low rates of interest. However, there is a chance that such a procedure, if handled improperly, might weaken the members' interest. It might cause the member to look on the cooperative as "the other fellows' " rather than "ours".

Financing might also be obtained from other sources such as the district banks for cooperatives of the Farm Credit System, commercial banks, utilities, insurance companies, other agricultural cooperatives, timber industries, or State and Federal developmental agencies. These are potential sources of both investment and working capital.

With the possible exception of State and Federal developmental agencies, rarely can more than 50 percent of the total investment be obtained from these outside sources. Each source usually requires a detailed, businesslike management plan for

the proposed operation, on which to base a financial analysis. In most instances, collateral and mortgages will be required to reduce the lending institution's risk.

The total amount of borrowed capital and the interest rate that can be sustained by the cooperative should be evaluated thoroughly. Relatively high interest rates, combined with the narrow profit margins that are characteristic of primary forest industries, can make loan repayment difficult. Yet, when funds are readily available, precautions should be taken not to overborrow and overcapitalize to the point of hampering operations with burdensome overhead expenses.

A sound practice is to design a financial structure flexible enough to withstand periods of unexpected financial difficulties. Financial problems can arise as a result of unusually harsh, perhaps unfair, competition during periods of reduced demand, or as a result of fluctuations or a downward trend in prices received for the end product.

Labor and Management

Except during World War II, forest cooperatives have encountered few labor problems. The most significant postwar problem has been a rapid turnover of labor due to the transitory nature of the work. Several pulpwood, Christmas tree, and maple syrup cooperatives, as well as a few sawlog cooperatives, have had difficulty hiring skilled and semiskilled labor. This has been due primarily to inability of these groups to provide reasonably stable or permanent employment. This problem can be expected in future operations unless the business can provide full-time year-round employment.

The availability of needed skills should be determined. If skilled labor is unavailable, a training program may be needed to develop the types of employees the cooperative needs. The estimated cost of such a program should be determined before beginning operations.

Management is vitally important to any cooperative, since it is responsible for planning, organizing, directing, coordinating, and controlling all of the business activities. Management is also responsible for hiring key personnel to carry out these functions.

Too often management's value has not been recognized in the actual organization and operation of cooperatives.

Ultimate control of a cooperative is invested in the membership, who can elect or remove the directors. However, management becomes the responsibility of the directors and general manager. Directors limit their activities to determining business policies and usually delegate most of the administrative responsibilities to a general manager. The general manager is the active business head of all operations and is thus responsible to members and directors for administering all business affairs.

Assuming that all other business factors are conducive to a successful operation, and without minimizing the importance of active members and directors to overall management, the general manager is the key to success of a forest-based cooperative. When the general manager is the only employee of the cooperative, he must have skills in forestry, administration, and public relations, and must also be a production manager, a marketing expert, and a good salesman. And, above all, the general manager must have the confidence of the industry with which he deals.

To carry out his duties most effectively, the manager of a year-round forest cooperative should have definite administrative authority, should be employed full-time, should be paid a competitive wage, should be offered an incentive bonus, should have no conflict of interest, and should be authorized to select qualified personnel for staff positions under his supervision.

And, except for marketing highly seasonal crops such as Christmas trees or maple syrup, no attempt should be made to operate until sufficient capital is raised to employ a full-time manager.

Costs and Returns

Assuming all other conditions are favorable for establishing a new cooperative, organizers must analyze its business potential before making capital investments. The nature and type of data required will vary by activity, area, economic conditions, and complexity of analysis. However, the following examples illustrate the basic factors to consider in making this determination.

Appropriate modifications should be made to suit prevailing conditions.

For a limited management cooperative.—The duties of the cooperative are to provide forest-management services, including stand inventories with periodic check cruises; prepare simple management plans; mark timber; supervise stand improvement; supervise stumpage sales and harvesting contracts; and recommend fire prevention practices and methods to control insects and diseases. These are the basic estimates for a one-man operation:

1. Maximum land area managed: 20,000 acres.
2. Minimum tract size handled: about 50 acres or 50,000 board feet, but dependent on stand characteristics.
3. Maximum workdays available per year: 250.
4. Estimated minimum first-year cost: $12,000. This includes $8,000 for a full-time forester, $2,600 for a part-time clerk and office space, and $1,400 for travel.

The minimum average cost would be $0.60 an acre per year or $12 an acre for a 20-year management program. Costs of a one-man operation can be expected to increase because of salary increases and rising overhead costs. These can be offset partially by increasing personnel productivity and acreage handled, and by skillfully manipulating the work load.

Based on the above activities and resources, a breakdown of annual tasks might appear as follows:

Tasks	*Man-days available*	*Acres covered*
Cruising timber*	100 days	5,000
Preparing management plans**	50 days	2,000
Marking timber***	50 days	1,000
Supervising sales****	50 days	—

*Aided by aerial photos; includes drawing maps and field plots, and making reports.
**Based on 100 tracts of 200 acres each.
***Based on a 20-year cutting cycle.
****25 weeks at 2 days per week.

Figuring a cut of 1,500 board feet in sawlogs plus 4 cords of pulpwood per acre, the drain and the stumpage value from 1,000 acres would be roughly:

Drain: Sawlogs—1,500,000 board feet.
Pulpwood—4,000 standard cords (128 cubic feet/cord).

Value of cut:		
Sawlog stumpage @ $20/M	$30,000
Pulpwood stumpage @ $1/cord	4,000
Total gross value	$34,000
or $34 per acre.	

These figures are rough estimates and for beginning years only. As growth improves, the annual sawlog cut may be doubled within 20 years. By then, the annual cut should be about 3,000 board feet per acre if annual growth has been 150 board feet per acre. This would double the gross return with less than a proportionate increase in management costs.

For a limited marketing cooperative.—The duties of the cooperative are to provide timber cruises and marking, sell stumpage, supervise harvest and initial transport, collect payments from buyers, settle members' accounts, and act as an advisor on these and other marketing problems. These are the basic estimates for a one-man operation:

1. Minimum acreage: 50,000 acres.
2. Minimum tract size handled: about 50 acres or 50,000 board feet, but dependent on stand characteristics.
3. Maximum man-days available per year: 250
4. Estimated minimum first-year cost: $12,000. This includes $8,000 for a forester-salesman, $2,600 for part-time clerk and office space, and $1,400 for travel.

An annual operations cost of $12,000 represents (1) about 14 percent of gross sales; (2) an average cost of 24 cents per acre under the program; or (3) about $4.80 for each acre marketed, based on a cut of 2,500 acres per year. How these costs are shared can be changed by changing the program's operations mix.

The marketing tasks may be divided as follows:

1. Marking timber: 125 man-days required to mark about 2,500 acres per year.
2. Selling timber and making contractual arrangements: about 20 days.
3. Supervising sales: 105 man-days, or 3 days per week for 35 weeks.

Figuring a cut of 1,500 board feet in sawlogs plus 4 cords of pulpwood per acre, the drain and stumpage value on 2,500 acres would be roughly:

Drain:	Sawlogs—3,750,000 board feet.	
	Pulpwood—10,000 cords.	
Value of cut:	Sawlog stumpage @ $20/M	$75,000
	Pulpwood stumpage @ $1/cord	10,000
	Gross value of cut	$85,000
		or $34/acre
Estimated return per acre to owner, based on:		
	Sawlog growth of 150 board feet/year @ $20/M	$3.00
	Pulpwood growth of ½ cord/year @ $1/cord	.50
	Total return	$3.50
	Less cost of sale	—.24
	Gross return	$3.26

These figures are for the beginning years. As growth improves, the annual sawlog cut may be increased.

For a limited management-marketing cooperative.—The duties of the association, assuming a two-man operation and emphasizing marketing services, are:

Under management agreement, to make stand inventories with periodic check cruises; prepare simple management plans; supervise stand improvement; and provide recommendations for production, protection, and sale.

Under marketing agreement, to negotiate with prospective buyers on prices and other terms of sale for timber produced under management agreement. Proceeds of sale are handled by the cooperative. After deducting commission, cooperative remits payment to member.

These are the basic estimates for a two-man operation:

1. Minimum forest-land area in program: 70,000 acres; all under marketing agreement and 20,000 acres under management agreement.
2. Maximum workdays available per year: 500 (250 professional and 250 technical).
3. Estimated minimum first-year cost: $20,000. This includes: $10,000 for a forester-salesman, $5,000 for an apprentice

forester, $2,600 for a part-time clerk and office, and $2,400 for travel.

The cost of operations can be allocated in this manner: (1) about 36 cents per year for each acre under management agreement, based on a 20,000-acre program; and (2) about $3.66 per acre harvested, based on a cut from 3,500 acres per year. The latter figure represents about 10.8 percent of gross sales. The cost calculations from which these figures were obtained are as follows:

1. Rough estimate to be charged for management: 150 workdays used per 20,000 acres per year @ $12,000 for 250 workdays = 3/5 of $12,000 or $7,200; $7,200 divided by 20,000 acres = $0.36/acre/year.
2. Rough estimate charged for marketing services: $20,000 total cost minus $7,200 management cost = $12,800 charged to marketing; $12,800 divided by 3,500 acres = $3.66 per acre harvested; or $12,800 divided by $119,000 gross receipts = 10.8 percent.

The management and marketing activities can be broken down as follows:

Tasks	*Man-days available*	*Acres covered*
Cruising timber*	100	5,000
Preparing management plans**	50	2,000
Marking timber***	175	3,500
Selling timber and arranging contracts	30	—
Supervising sales****	145	—

*Aided by aerial photos; includes drawing maps and field plots, and making reports.
**Based on 100 tracts of 200 acres each.
***Based on a 20-year cutting cycle.
****48 weeks at 3 days per week.

Figuring a cut of 1,500 board feet in sawlogs plus 4 cords of pulpwood per acre from 3,500 acres of timberland, the drain and stumpage could be roughly:

Drain:	Sawlogs—5,250,000 board feet.	
	Pulpwood—14,000 standard cords.	
Value of cut:	Sawlog stumpage @ $20/M	$105,000
	Pulpwood stumpage @ $1/cord	14,000
		$119,000

These figures are for the beginning years only. If future annual growth averages 150 board feet per acre, the annual sawlog cut may be doubled within 20 years.

For a limited processing-marketing cooperative.—Many structural and operational variations are possible for this type of organization. Also, considerable data describing these variations are available. Thus, this discussion is limited to suggesting some minimum (rule of thumb) requirements for Appalachian hardwood producing units:

1. Output: 3 to 5 million board feet per year.
2. Acreage harvested: 2,000 to 3,400 acres per year with a periodic cutting of 1,500 board feet per acre.
3. Program: Based on expected annual drain, 40,000 to 68,000 acres would be needed to support a 20-year program of cutting to supply the above mill capacity.

With an annual growth rate of 150 board feet per year, only one-half as much acreage would be needed within 20 years to supply the mill to its capacity. Or, the mill could increase its capacity at the same rate as the increase in the timber resource and double its capacity within 20 years.

ORGANIZATIONAL CONSIDERATIONS

An organization's formal and legal structure and its operating methods and policies significantly influence its performance. Structural aspects of a cooperative include such factors as determining the purpose, objectives, and scope of business operations in keeping with the character of ownership; separating activities logically and setting up distinct functional divisions; delegating formal authority and assigning specific duties and responsibilities; establishing required staff positions and committees; developing policies and procedures for major activities; and selecting qualified personnel.

The data collected and evaluated during the preorganizational stage serve as the basis for developing a cooperative's structure and operating policies. The following discussion explores some

of the more important legal factors as they apply to organizing forestry cooperatives.

Assistance Available

It may be necessary to confer with persons who have practical experience in cooperatives and forest technology before deciding what form and plan of operation to use. Assistance can be obtained from county agricultural agents, state and county foresters, consulting foresters, universities, agricultural cooperatives, and the Farmer Cooperative Service of the U.S. Department of Agriculture. Forestry cooperative advisory groups established in 26 states can also provide valuable assistance.

Legal Structure

Legal counsel should be retained to help draw up the organizational documents. Counsel should be especially knowledgeable about both Federal and State laws and regulations governing cooperatives.

Each state has one or more statutes regulating the incorporation of new business organizations. Counsel should make a careful investigation to determine the statute under which the proposed cooperative should be incorporated. A copy of these statutes can be obtained from the proper state official, usually the secretary of state or corporation commissioner.

You will want to consider with your attorney the advantages and disadvantages of operating as a profit or nonprofit enterprise in terms of your cooperative's basic objectives, tax structure, and ability to finance, as well as the expected attitudes of prospective members and business associates.

Incorporation.—Some forestry cooperatives that went out of business were voluntary, unincorporated organizations. This form of loosely knit organization has proved to be an unstable business form even for businesses not cooperatively owned and operated. A group that plans to establish a forestry cooperative should therefore give serious consideration to incorporating.

There are no appreciable disadvantages to incorporating a business. In contrast, there are several advantages. Probably the main advantage is the legal protection it gives its members. By virtue

of being incorporated, the organization gains legal entity and provides limited liability for its members. The corporation is responsible for debts and other liabilities incurred, is able to enter into contracts, and is able to obtain title to property. An incorporated firm can also be authorized to sell stock and can often borrow funds easier than the unincorporated firm. The cost of incorporation is usually negligible.

Charter and bylaws.—In drafting the legal papers, care must be taken to preserve the association's cooperative character by adopting suitable provisions in the charter, articles, and bylaws. Each state has statutes governing the incorporation of cooperatives, which require inclusion of specific information on the charter or certificate. The specific requirements vary from state to state. Also, petitioning cooperatives often include additional information in the form of articles of incorporation and bylaws as a part of the official record.

The articles pertain to the general structure of the cooperative. They usually include the name, place of business, purpose, amount and number of shares of capital stock to be issued, rules governing the transfer of stock, period of existence, number of directors and their duties, property rights of the members, and certain other provisions consistent with the laws of the state.

Bylaws of a cooperative comprise a comprehensive set of rules that regulate its day-to-day business activities. The bylaws should be composed with meticulous detail since they express exactly how the business is to be conducted, and point out the responsibilities of its members, directors, and other officers, requirements for membership, voting rights and quorums, determination and distribution of earnings, and miscellaneous provisions.

Authority delegated by members.—Regarding organization and operation, consider the degree of control a forestry cooperative should have over its members' forest land. Should legal authority be delegated to the cooperative to manage its members' woodlands; and, if so, to what degree? Should management and marketing agreements be short-term or long-term contracts or a judicious combination of both?

Most forest cooperatives in the United States were organized

with a very limited management control of timber supply rather than as associations with full contractual authority. The latter type of control is more prevalent in Europe, where landowners and other primary producers have practiced cooperative enterprise successfully for over a century.

Such contractual arrangements are not foreign to this country, however. Landowners, especially nonresidents, commonly place their holdings under the direction of trusts, banks, law firms, and similar organizations. These contracts range from short to long and often indefinite periods of time, confer varying degrees of legal authority, and cover activities ranging from simple safekeeping to continuous business-operations management.

Other landowners might also welcome a similar opportunity. By managing their lands through an association of owners, they would stand to gain monetarily and still maintain some personal control. First, they would gain the advantage of having their lands under the business direction of professional forest managers. Second, their business should be able to operate with increasing profitability as it increases in size and flexibility. And third, management control by the cooperative would permit nonresident owners to keep their property under continuous and productive management.

Indirectly, owners would get other advantages from the cooperative's improved business activities. To a cooperative performing management, processing, or marketing activities for small woodland owners, there are several obvious business advantages to the cooperative if complete control is held over the timber resource and its disposition. Activities such as woodland management, harvesting, transporting, processing, sales and distribution can be programmed in accordance with the cooperative's production and marketing objectives and commitments. Under able management, such a cooperative should be more flexible, be able to plan ahead, have fewer problems communicating with its members, avoid many of the characteristic problems and pitfalls of cooperatives that have limited short-run authority, and, in the final analysis, be more efficient.

Perhaps one of the main drawbacks to forming a cooperative

that has full management control would be the loss by members of personal day-to-day control over their woodlands. Some prospective members may oppose turning this much control over to cooperative management since it would require giving up freedom of action to manage their forests as they see fit. Consequently, except under short-run agreements, their participation could not be expected.

Working agreements.—Particular attention should be given to the membership, management, and marketing agreements to be used. Although many different types of written and verbal contracts will be required during the life span of an organization, two are fairly basic to a new cooperative: preorganizational contracts and operating agreements.

The preorganizational contract is an agreement between the cooperative and prospective members. Generally this is a written agreement in which the prospective member guarantees to actively participate or to provide a minimum volume, capital, or both, should the forestry association actually become established. Such a commitment by prospective members affords the organizers a valid basis upon which to plan, borrow, and conduct further organizational activities. If prospective members will not provide the required initial capital, expenses incidental to incorporating will not be incurred.

The second type of organizational document includes basic operating agreements such as management and marketing contracts. These may cover a wide range of activities on the part of both parties. However, they should set forth clearly the responsibilities of both the member and the cooperative in carrying out prescribed activities, and the manner in which these activities are to be financed.

Sample working agreements may be obtained from state departments of agriculture and commerce, extension services, agricultural cooperatives, and the State Forestry Cooperative Advisory Group. We suggest: (1) that sample documents be closely reviewed for their applicability, (2) that legal counsel be retained for drafting new documents, and (3) that all contracts be definitive, understandable, and reasonably airtight to assure a complete meeting of minds.

A cooperative enterprise, in itself, cannot guarantee success. A cooperative is simply another way of doing business. Like the individual proprietorship, partnership, or general corporation, owners of a cooperative must found their organization on a businesslike basis if they are to succeed.

Organizers of a forest-based cooperative can avoid or solve the more serious operational problems if, before organizing, they will: (1) adopt specific guidelines and determine the economic need for the enterprise; (2) conduct an objective study of the operations' short- and long-run business potential; and (3) develop a comprehensive plan for both its organization and operation.

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Selected References

Cope, Joshua A.
1943. Farm Forestry in the Eastern United States. 40 pp., illus. Charles Lathrop Pack Forestry Found., Washington.

Cunningham, Russell N.
1947. Forest Cooperatives in the United States. U. S. Forest Serv. Reappraisal of the Forest Situation Rep. 6, 48 pp.

Dempsey, Gilbert P.
1968. Some New Guidelines for the Forest Cooperatives. J. Forestry 66: 17-22.

Dempsey, Gilbert P.
1967. Forest Cooperatives: A Bibliography. U. S. Forest Serv. Res. Paper NE-82, 53 pp. NE. Forest Exp. Sta., Upper Darby, Pa.

Duerr, William A., and Henry J. Vaux.
1953. Research in the Economics of Forestry. 475 pp., illus. Charles Lathrop Pack Forestry Found., Washington.

Francois, T.
1956. Forestry Associations. Unasylva 10(2): 57-108.

Henning, George F., and R. E. Laubis.
1961. Financial Structure of Agricultural Business Organizations. Ohio Agr. Exp. Sta. Res. Bull. 880, 54 pp., illus.

Hulbert, L. S., and Raymond J. Mischler.
1958. Legal Phases of Farmer Cooperatives. U. S. Dep. Agr. Farmer Coop. Serv. Bull. 10, 376 pp., illus.

Knapp, Joseph G.
1963. Farmers in Business: Studies in Cooperative Enterprise. 450 pp., illus. American Inst. Cooperation, Washington.

Larson, Willie G.
1963. Contract Farming and Vertical Integration, 1953-1962 — A List of Selected References. U. S. Dep. Agr. Nat. Agr. Libr., Library List 64, 77 pp.

Lord, William B.
1963. A Reconsideration of the Farm Forestry Problem. J. Forestry 61: 262-264.

Markeson, Clyde B.
1965. Identifying the Need for Forestry Associations. U. S. Dep. Agr. Farmer Cooperative Serv. Educ. Circ. 20, 6 pp., illus.

Mead, Walter J.
1964. Mergers and Economic Concentration in the Douglas-Fir Lumber Industry. U. S. Forest Serv. Res. Paper PNW-9, 81 pp., illus.

Mischler, Raymond J., and John F. Donogue.
1961. State Statutes Authorizing Assistance to Farmer Cooperatives. U. S. Dep. Agr., Farmer Cooperative Serv. Inform. Bull. 22, 22 pp.

Mueller, W. F., and J. M. Finley.
1958. Membership Marketing Contacts of Agricultural Cooperatives in California. Calif. Agr. Exp. Sta. Bull. 760, 63 pp., illus.

Quinney, Dean N.
1964. Small Private Forestland Ownership in the United States —Individual and Social Perception. Natural Resources 3(3): 379-393.

Rettie, J. C., and F. A. Ineson.
1950. Otsego Forest Products Cooperatives Association of Cooperstown, New York—An Evaluation. U. S. Dep. Agr. Inform. Bull. 17, 42 pp., illus.

Rust, Irwin W.
1965. How to Start a Cooperative. U. S. Dep. Agr. Farmer Cooperative Serv. Educ. Circ. 18, 18 pp., illus.

Savage, Job K., and David Volkin.
1965. Cooperative Criteria. U. S. Dep. Agr. Farmer Cooperative Serv. Rep. 71, 11 pp., illus.

Schallau, Con H.
1964. Forest Owners and Timber Management in Michigan. U. S. Forest Serv. Res. Paper LS-9, 39 pp., illus.

Solin, Lawrence.
1940. A Study of Woodland Cooperatives in the United States. New York State College of Forestry, Bull. 13(2): 117 pp., illus.

Stanton, Beryle E.
1963. Farmer Cooperatives—Farm Business Tools. U. S. Dep. Agr. Farmer Cooperative Serv. Agr. Inform. Bull. 275, 58 pp., illus.

Stoddard, Charles H.
1961. The Small Private Forest in the United States. 171 pp., illus. Resources for the Future, Inc., Washington.

United States Department of Agriculture.
1965. Forestry Cooperatives: USDA Workshop Proceedings at

DENVER, COLO. AND PRINCETON, W. VA. U. S. Dep. Agr. Misc. Pub., 94 pp., illus.

United States Department of Agriculture.
1967. FORESTRY COOPERATIVES WORKSHOP PROCEEDINGS. U. S. Dep. Agr. Misc. Pub., 43 pp.

United States Farmer Cooperative Service.
1965. FARMER COOPERATIVES IN THE UNITED STATES. U. S. Dep. Agr. Farmer Cooperative Serv. Bull. 1, 374 pp., illus.

United States Farmer Cooperative Service.
1965. SAMPLE LEGAL DOCUMENTS FOR NEW COOPERATIVES. U. S. Dep. Agr. Farmer Cooperative Serv. Educ. Circ. 19, 28 pp., illus.

Zimmerman, Eliot W., and Clyde B. Markeson.
1963. TWENTY YEARS' PROGRESS OF AUSABLE FOREST PRODUCTS ASSOCIATION. U. S. Dep. Agr. Farmer Cooperative Serv. and Forest Serv. Inform. Bull. 35, 29 pp., illus.

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THE FOREST SERVICE of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

by S. Little

LOCAL SEED SOURCES

Recommended for Loblolly Pine in Maryland and Shortleaf Pine in New Jersey and Pennsylvania

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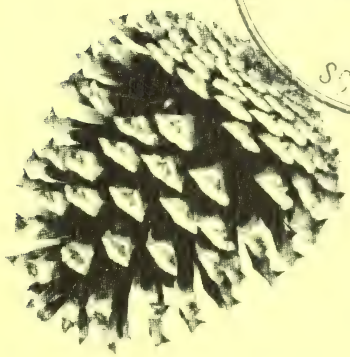

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
RICHARD D. LANE, DIRECTOR

THE AUTHOR

SILAS LITTLE is principal silviculturist in the Upper Darby headquarters office of the Northeastern Forest Experiment Station. He earned a Bachelor of Science degree from Massachusetts State College in 1935, a Master of Forestry degree in silviculture and soils from Yale University in 1936, and a Ph.D. degree in silviculture and ecology from Yale in 1947. He joined the Forest Service in 1936, and has spent most of his career working on fire and silviculture research in New Jersey, Maryland, and eastern Pennsylvania.

LOCAL SEED SOURCES have proved best for establishing loblolly pine stands in Maryland and shortleaf pine stands in New Jersey and Pennsylvania. In studies conducted by the U. S. Forest Service, local seed sources provided trees that were better adapted to local climates than stems that had originated from seed collected at various locations in the South. And the trees from local seed sources also grew much faster than the trees from the southern seed sources.

This research was sponsored by the Southern Forest Tree Improvement Committee (SFTIC), which includes in its membership representatives from the wood-product industries, State forestry departments, universities, and the U. S. Forest Service. A SFTIC subcommittee has been conducting a study of the geographic source of seed for many years. Other subcommittees have

been studying tree selection and breeding, progeny testing, and genetic control of seed. These subcommittees have prepared publications and have suggested and supervised cooperative studies.

In 1951, SFTIC began a pine seed-source study throughout the South. As part of this study, the Northeastern Forest Experiment Station established, between 1953 and 1958, a loblolly pine plantation in eastern Maryland and some shortleaf pine plantations in south-central Pennsylvania and southern New Jersey. Each plantation contained seedlings from several geographic sources. This report describes the results obtained from measurements made between the 1967 and 1968 growing seasons in these plantations.

Seedlings were planted at 6-foot spacings in 0.1-acre plots. One plot of each source constituted a block, and each plantation contained four blocks. We measured only the inner 49 seedlings of the 121 planted in each plot.

Seed for the loblolly pine plantation in Maryland came from one Maryland source and eight other sources in Alabama, Arkansas, Georgia, Louisiana, North Carolina, and Texas. Seedlings were grown in the Maryland State Forest Nursery at Harmans; they were then planted in 1953 as 1-0 stock in a field that had been tilled the previous year, in the Pocomoke State Forest, Worcester County.

Seed for the shortleaf pine plantation in New Jersey came from one New Jersey source and six other sources in Georgia, Louisiana, Missouri, South Carolina, Tennessee, and Virginia. Seedlings were grown at the New Jersey State Nursery at Washington Crossing and were planted in 1958 as 2-0 stock on a former nursery site in the Green Bank State Forest, Burlington County.

Seed for the shortleaf pine plantations in Pennsylvania came from one Pennsylvania county and nine other counties in Arkansas, Georgia, Oklahoma, Tennessee, and Texas. Both a 1954 and a 1958 plantation were established, with different sources for each plantation. The 1958 plantation was established because initial survival was low in the 1954 plantings. All seedlings planted in

1954 had been raised in the Mont Alto Nursery of the Pennsylvania Department of Forests and Waters. All seedlings planted in 1958 had been grown in the Washington Crossing Nursery of the New Jersey Bureau of Forestry. In both years 2-0 stock was planted in abandoned fields.

Loblolly Pine in Maryland

Survival of loblolly pines from certain southern sources has been relatively low, probably because of repeated winter injury and snow breakage. The two stocks most seriously affected are from Georgia and Louisiana sources, and these had survival rates of 47 and 53 percent, respectively, after 15 years (table 1). Similar, but less extensive, injuries have reduced the stocking of North Carolina and Texas sources. If the study plots had not been located well within a field that was planted to pines in 1953, even lower survival would probably have occurred.

Surprisingly, the Arkansas source has had the best survival: 84 percent. Maryland and two northern Alabama sources had 73

Table 1.—*Fifteen-year survival, and the average diameter, height, basal area, and merchantable volume of living stems, by seed source of loblolly pine*

Seed source	Survival	Average diameter[1]	Average height	Basal area per acre	Volume per acre[2]
	Percent	*Inches*	*Feet*	*Sq. Ft.*	*Cords*
Somerset Co., Md.	73	5.7	39.1	160.5	27.8
Pamlico Co., N. C.	58	6.1	38.1	141.7	24.1
Onslow Co., N. C.	62	5.7	36.4	134.7	21.5
Jefferson Co., Ala.	71	5.7	35.7	152.3	23.4
Cullman Co., Ala.	73	5.7	35.6	159.6	24.6
Clark Co., Ark.	84	5.6	34.0	176.0	25.3
Wilcox and Crisp Cos., Ga.	47	5.8	33.1	106.1	15.1
Angelina Co., Texas	67	5.8	32.5	151.5	21.5
Livingston Parish, La.	53	5.4	30.3	103.2	13.3

[1]In this and subsequent tables average diameter is that of the tree of mean basal area.
[2]Based on measured diameter and height and table 3 of U.S. Dep. Agr. Misc. Pub. 50. Volumes are in cords of rough wood above a 1-foot stump to a diameter (i.b.) of 3 inches. Trees less than 4.0 inches in diameter (b.h.) were excluded.

or 71 percent of the planted seedlings still living after 15 growing seasons.

Maryland seedlings were the tallest in the 15-year-old planting. They led in: (1) average height of all surviving seedlings, (2) average height of the tallest five trees per plot, and (3) maximum height (tables 1 and 2). In all these height characteristics, the local source was followed rather closely by the North Carolina sources and less closely by the northern Alabama sources. Trees from Arkansas, Georgia, Texas, and Louisiana seed were still shorter, the maximum difference among sources being 7 to 9 feet.

Height differences among sources did not increase in the last 5 years, even though there were some shifts in relative rankings. Maximum differences among sources in the average height of all surviving trees were 8.5 feet at 10 years and 8.8 feet at 15 years. In average height of the tallest five trees per plot, maximum differences were 7.4 and 7.0 feet, respectively.

Differences among sources in the average diameter of all surviving trees and of the tallest 123 trees per acre were not great at 15 years, the maximum difference for each group being only 0.7 inch (tables 1 and 2). Average diameters were affected by

Table 2.—*Fifteen-year average height and diameter of the tallest five trees per plot, and maximum height, by seed source of loblolly pine*[1]

Seed source	Average height	Maximum height	Average diameter (b.h.)
	Feet	*Feet*	*Inches*
Somerset Co., Md.	44.1	48	6.8
Pamlico Co., N. C.	43.0	47	6.9
Onslow Co., N. C.	41.7	45	7.1
Jefferson Co., Ala.	40.0	42	6.8
Cullman Co., Ala.	41.0	44	7.1
Clark Co., Ark.	38.4	40	6.7
Wilcox and Crisp Cos., Ga.	38.6	42	7.4
Angelina Co., Texas	38.2	41	7.4
Livingston Parish, La.	37.1	43	6.9

[1]Because measurements were limited to inner 42-foot square of each 0.1-acre plot, 5 trees per plot are equivalent to 123 per acre.

stocking, tending to be larger in sources with relatively low survival (North Carolina, Georgia, and Texas).

Basal area per acre 15 years after planting varied by source from 103 to 176 square feet. Louisiana and Georgia stocks had the lowest basal areas, while the Arkansas source had the highest. The Maryland source, with 160 square feet, exceeded North Carolina stocks by 19 to 26 square feet (table 1).

The local (Maryland) source had the greatest merchantable volume of rough pulpwood at 15 years, about 28 cords per acre (table 1). That volume was about twice the amount produced by Louisiana or Georgia sources, and 2.5 cords more than the second-best source, Arkansas (table 1).

During the 15-year tally, records were kept on: (1) trees that lacked a terminal shoot or leader; (2) those with double stems, if both shoots were still living; (3) occurrence of *Cronartium* cankers on the boles; (4) trees with crooked or very crooked boles; and (5) leaning stems. Only 26 percent of the surviving Maryland trees had such defects (table 3). The Arkansas source

Table 3.—*Proportion of living loblolly pines with various observed defects in 1967, by seed source*

Seed source	Living stems					
	Lacking terminal	With double terminal[1]	With cankers on lower bole[2]	With crooked or very crooked boles	Leaning boles	One or more defects
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Somerset Co., Md.	6	9	1	11	0	26
Pamlico Co., N. C.	5	2	25	34	0	56
Onslow Co., N. C.	7	1	17	15	1	32
Jefferson Co., Ala.	5	6	14	37	0	54
Cullman Co., Ala.	13	9	14	20	0	44
Clark Co., Ark.	3	9	1	15	0	27
Wilcox and Crisp Cos., Ga.	8	9	25	35	3	66
Angelina Co., Texas	6	10	5	21	1	41
Livingston Parish, La.	7	5	9	9	15	35

[1]Limited to stems with both shoots still living. On many of the stems that fork in the lower bole, one shoot was already dead, and these trees were not included.

[2]Caused by *Cronartium fusiforme* or *Cronartium cerebrum*. Cankers caused by both were present, but could not always be separated.

was next with 27 percent, and both of those sources excelled in low incidence of stem cankers. Cankers caused by *Cronartium fusiforme* or *C. cerebrum* were common in the North Carolina, Georgia, and Alabama sources—occurring on 14 to 25 percent of the surviving trees. Breakage at cankers had already been an important factor in reducing survival of the North Carolina sources, and more losses in the affected sources can be expected from breakage at cankers. Bending from wet snows has been most common in the Louisiana source. Crooked stems were especially prevalent, affecting 34 to 37 percent of the trees from one North Carolina source, one Alabama source, and the Georgia source.

Figure 1.—Shortleaf pines from Missouri and New Jersey seed in the New Jersey plantation after 11 growing seasons. Pipe post in the foreground marks the boundary between Missouri trees on left and New Jersey trees on the right. Note the higher survival and greater size of trees from the New Jersey source.

Table 4.—*Ten-year survival, average diameter and average and maximum heights of living trees, and basal area per acre, by seed source of shortleaf pine in the New Jersey plantation*

Seed source	10-year survival	Average diameter	Average height	Maximum height	Basal area per acre
	Percent	*Inches*	*Feet*	*Feet*	*Sq. ft.*
Burlington Co., N. J.	94	3.6	17.8	25	79.2
Anderson Co., Tenn.	70	3.1	14.2	21	43.2
Dent Co., Mo.	70	3.0	13.8	20	41.9
Southampton Co., Va.	49	2.9	13.0	19	28.4
Union Co., S. C.	34	2.6	11.5	17	14.6
Webster Co., Ga.	25	2.0	8.6	18	6.9
St. Helena Parish, La.	19	2.1	9.9	16	5.3

Shortleaf Pine

In New Jersey.—Seedlings from the local New Jersey source had the best survival, the largest stems in diameter and height, and the most basal area per acre at 10 years after planting (table 4 and figs. 1 to 3). In fact, the differences among sources are outstanding. Few stems in the two most southern sources were still living in 1968, and these were 1.5 inches smaller in diameter and 8 to 10 feet shorter than trees of local origin. Even the second-best sources, Tennessee and Missouri, had only about half as much basal area per acre at 10 years as the local trees.

Table 5.—*Ten-year average height and diameter of the tallest five shortleaf pines per plot, by seed source in the New Jersey plantation*

Seed source	Average height	Average diameter
	Feet	*Inches*
Burlington County, N. J.	22.0	4.3
Anderson County, Tenn.	18.9	4.0
Dent County, Mo.	17.4	3.8
Southampton County, Va.	16.2	3.7
Union County, S. C.	13.2	3.1
Webster County, Ga.	10.5	2.5
St. Helena Parish, La.	11.1	2.4

Figure 2.—Shortleaf pines from New Jersey and Tennessee seed in the New Jersey plantation after 11 growing seasons. Pipe post in front of the man marks the boundary between New Jersey trees on left and Tennessee trees on right. Note the higher survival and greater size of trees in the New Jersey source.

When crop trees or the largest five trees per plot (123 per acre) are considered, the local source still leads. Its crop trees were 3 feet taller than the next best source, and 11.5 feet taller than the poorest source (table 5).

Most of the differences among sources in survival and growth may be due to stem damage from wet snows or to winter injury of foliage. The southern sources have far more leaning stems from the past snow damage (table 6). Even after 10 years' growth in the New Jersey plantation, shortleaf pines of southern origin still suffer severe winter injury to the foliage. The following proportions of living stems had appreciable amounts of winter injury to foliage in April 1968:

Source	*Percent*
Burlington County, N. J.	0
Dent County, Mo.	7
Anderson County, Tenn.	18
Southampton County, Va.	28
Union County, S. C.	70
Webster County, Ga.	80
St. Helena Parish, La.	76

In Pennsylvania.—Seedlings from Franklin County, Pennsylvania, had the best survival, largest average diameter and height, and the most basal area per acre (table 7). However, they were closely followed by seedlings of the Tennessee source; and when only crop trees are considered, the Tennessee seedlings slightly outgrew the Pennsylvania trees in the 1954 planting, but not in the 1958 plantation (table 8).

Figure 3.—Shortleaf pines from Louisiana and New Jersey seed in the New Jersey plantation after 11 growing seasons. Note the very low survival and short height of Louisiana trees in the foreground, when compared with New Jersey trees in the background.

Table 6.—*Proportion of living shortleaf pines with observed defects in 1968, by seed source in the New Jersey plantation*

Seed source	Broken terminal[1]	Double terminal[2]	Crooked or very crooked boles	Leaning stems	One or more defects
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
Burlington County, N. J.	5	6	3	4	17
Anderson County, Tenn.	6	4	1	11	21
Dent County, Mo.	0	4	1	2	7
Southampton County, Va.	4	11	1	15	30
Union County, S. C.	3	8	0	21	30
Webster County, Ga.	0	4	6	24	33
St. Helena Parish, La.	0	8	8	16	32

[1]Mostly of recent occurrence, from wet snow in winter of 1967-68.
[2]Limited to stems with both shoots still living.

Table 7.—*Survival, average diameter, and average and maximum heights of living shortleaf pines, and basal area per acre (after 10 or 14 years), by seed source in the Pennsylvania plantations*

Plantation and seed source	Survival	Average diameter (b.h.)	Average height	Maximum height	Basal area per acre
1958 Plantation	*Percent*	*Inches*	*Feet*	*Feet*	*Sq. ft.*
Franklin County, Pa.	41	1.8	8.5	14.0	8.8
Anderson County, Tenn.	36	1.3	7.5	13.6	3.7
McCurtain County, Okla.	27	1.0	6.5	12.1	1.7
Clarke County, Ga.	22	.9	6.1	11.8	1.2
Cherokee County, Texas	7	1.0	6.1	11.1	.4
Ashley County, Ark.	3	.3	4.6	6.3	.01
1954 Plantation					
Franklin County, Pa.	35	2.3	9.8	16.3	11.7
Morgan County, Tenn.	31	2.1	9.8	16.1	9.2
Stone County, Ark.	11	1.6	8.2	12.1	2.0
Pushmataha County, Okla.	5	.8	5.5	8.8	.2
Ashley County, Ark.	3	1.3	7.5	9.0	.3
Angelina County, Texas	1—	.6	6.6	6.6	.0+

In both the 1954 and the 1958 plantations two or three of the southernmost sources had very poor survival—less than 10 percent in 1968. Deer browsing may have affected the survival and growth of seedlings from all sources, but it is considered less important than winter injury.

Winter injury was still a common occurrence 10 or 14 growing seasons after planting on seedlings from out-of-state sources (table 9). All surviving seedlings in the Texas and the Ashley County, Arkansas, sources in both plantations had severe winter injury in 1968. Not only was most of the foliage killed, but the terminal shoots of some seedlings were also killed. Tennessee trees were noticeably less affected than other out-of-state sources, but about 95 percent of the Tennessee stems had conspicuous damage in both plantations. In contrast, only 5 to 15 percent of the Pennsylvania trees suffered winter injury, which was light and affected only some of the foliage on these stems.

Table 8.—*Average height and diameter of tallest five shortleaf pines per plot after 10 or 14 years, by seed source in the Pennsylvania plantations*[1]

Plantation and seed source	Average height	Average diameter (b.h.)
1958 Plantation	*Feet*	*Inches*
Franklin County, Pa.	10.8	2.4
Anderson County, Tenn.	9.4	1.6
McCurtain County, Okla.	7.0	1.2
Clarke County, Ga.	7.5	1.3
Cherokee County, Texas	6.3	1.0
Ashley County, Ark.	4.6	.3
1954 Plantation		
Franklin County, Pa.	12.1	2.9
Morgan County, Tenn.	12.9	3.0—
Stone County, Ark.	8.9	1.8
Pushmataha County, Okla.	5.5	.8
Ashley County, Ark.	7.5	1.3
Angelina County, Texas	6.6	.6

[1]In plots containing less than 5 trees, averages are based on all living trees.

Table 9.—*Proportion of living shortleaf pines with observed defects or winter injury in 1968, by seed source in the Pennsylvania plantations*

Plantation and seed source	Double terminal	Crooked or very crooked boles	Winter injury	
			Severe	Light
1958 Plantation	*Percent*	*Percent*	*Percent*	*Percent*
Franklin County, Pa.	2	0	0	5
Anderson County, Tenn.	0	0	30	64
McCurtain County, Okla.	8	0	69	27
Clarke County, Ga.	0	2	61	34
Cherokee County, Texas	0	0	100	0
Ashley County, Ark.	0	0	100	0
1954 Plantation				
Franklin County, Pa.	0	0	0	15
Morgan County, Tenn.	3	0	8	89
Stone County, Ark.	5	0	64	36
Pushmataha County, Okla.	0	0	80	20
Ashley County, Ark.	0	0	100	0
Angelina County, Texas	0	0	100	0

The 15-year results on planting loblolly pine in Worcester County, Maryland, verify these earlier conclusions:

- Trees from the westernmost sources and from the northeastern source were least infected with stem (fusiform) rust *(Wells and Wakeley 1966)*. In the Maryland planting this was true: 1 percent of the Maryland and Arkansas trees, 5 percent of the Texas trees, and 9 percent of the Louisiana trees had stem cankers in 1968, compared with 14 to 25 percent of the living trees in the Alabama, North Carolina, and Georgia sources. Wells and Wakeley *(1966)* suggested that the resistance of Maryland trees might be due to introgression with pond or shortleaf pines, which are resistant species. I feel that there might be such introgression even though no characteristics of pond or shortleaf have been observed in the planted trees of Maryland source.

- Trees of western origin survived best in most plantings *(Wells and Wakeley 1966)*. This was partially true in that highest sur-

vival was in the Arkansas source. However, Texas and Louisiana trees had lower survival than Maryland or Alabama trees.

- Local seed can be recommended without qualification for plantings in Maryland *(Wells and Wakeley 1966; Little and Somes 1964)*. Trees of local origin have survived well, are taller, have the most volume per acre, and had the fewest defects at 15 years; so they continue to look far more promising than stems from the out-of-state sources.

Ten-year results from planting shortleaf pines in southern New Jersey are similar to the Maryland results with loblolly pine although the advantages of using local seed sources in New Jersey are even more striking. The local shortleaf seed source has provided: (1) seedlings with an appreciably higher rate of survival (94 percent compared to 70 percent for the next best source), (2) taller stems with larger diameters, (3) almost twice as much basal area per acre as the second-best sources, and (4) stems more resistant to winter injury of foliage. Tennessee and Missouri sources did seem about as resistant to damage from wet snows as the local stock, but were appreciably behind the New Jersey trees in all other respects.

Shortleaf pine growth in the Pennsylvania plantations near Blain has been unusually slow. Even the local sources have attained an average height of only 8.5 feet and a maximum height of only 14 feet after 10 years—compared with 17.8 and 25 feet, respectively, in the New Jersey plantation. The heights at Blain indicate a site index of only about 30 feet at 50 years, when the curves of Coile and Schumacher *(1953)* are applied. In comparison, data from natural stands of shortleaf pine near Mont Alto in Franklin County *(Aughanbaugh 1950)* indicate site index there of 55 to 60 feet at 50 years.

The fact that volunteer Virginia pines have outgrown the planted shortleaf pines at Blain is a further indication that shortleaf growth there has been below normal. From my observations, shortleaf pine in its early life grows just as rapidly as Virginia pine in sections where both occur. Aughanbaugh *(1950)* has

stated that shortleaf pine is generally dominant in mixtures with Virginia pine on favorable sites in southeastern Pennsylvania.

The poor behavior of shortleaf pine near Blain raises questions as to the cause. Part of the slow growth of Pennsylvania trees there may be inherent: Dr. O. O. Wells, of the Southern Forest Experiment Station, reports that shortleaf pines of the Pennsylvania source have had considerably slower growth than the shortleaf pines of New Jersey stock in all plantings of the southern pine seed source study.[1] However, such an explanation does not account for the observed difference in growth between the Mont Alto and Blain areas. Deer browsing is another factor that may have reduced survival and growth of the Blain shortleaf pines, but the surviving trees that have outgrown the reach of deer are still growing at a very slow rate.

Is Blain outside the natural range of shortleaf pine, thus accounting for the slow growth? According to a map prepared by Elbert Little and published by Fowells *(1965),* shortleaf pine occurs rarely in Pennsylvania—mostly near the southern border in Franklin and Adams Counties. However, four small outlying occurrences are indicated north of Blain.

Although there seems to be general agreement that the best shortleaf pines occur in Franklin and Adams Counties, several investigators have reported trees or stands outside these counties. Aughanbaugh *(1950)* reported outlier stands or specimen trees as far north as Mifflinburg, Selinsgrove, and Sunbury. Professor Rex Melton of The Pennsylvania State University indicated that shortleaf pine has been found in Bedford County, and in one area in central Huntingdon County.[1] Perry *(1924)* reported the occurrence of shortleaf pine near McConnellsburg in Fulton County, while Shafer and Chisman *(1957)* found two trees in Montour County and excellent stems on Warriors Ridge in Huntingdon County.

Nevertheless, the occurrence of this species in Pennsylvania is discontinuous, and limited to sites that have favorable soils and microclimate. Shafer and Chisman *(1957)* suggested that in Huntingdon County shortleaf pine is confined to southern aspects on

[1]In personal correspondence with the author.

sandstone soils. Professor Melton stated that sandy soils seem necessary for shortleaf pine in Pennsylvania; and only on such soils is shortleaf more productive than pitch, Virginia, or table-mountain pines.[1] In his opinion, valleys that form frost pockets, and high elevations, should be avoided in the Ridge and Valley Province. Aughanbaugh *(1950)* recommended planting shortleaf pine in Perry County and certain other counties only at elevations of less than 1,000 feet in intermountain valleys.

Although Blain is in one of the intermountain valleys of Perry County recommended by Aughanbaugh, it seems probable that the poor performance of our planted pines there is due to a combination of unfavorable soil and microclimate. The 1954 plantation is on a gently sloping portion of the valley floor; the 1958 plantation is on a small knoll. Both are on shale soils: the 1954 plantation on a cobbly loam with fair surface drainage and imperfect-to-poor subsurface drainage; the 1958 planting on a shallow shaly slit loam that has good surface and subsurface drainage. Sandy soils might have permitted better growth. Microclimate at Blain may also have favored more winter injury than would have occurred in protected locations on southerly aspects.

Both Professor Melton and I recommend that any plantings of shortleaf pine in the Ridge and Valley Province of Pennsylvania be experimental until their value is demonstrated. On the basis of the 1968 results reported in this paper, and other observations, more extensive use of this species should be limited largely to sandy soils of southeastern Pennsylvania, especially to such sections as Franklin County where shortleaf pine occurs naturally and has produced good stands.

In southeastern Pennsylvania, local trees probably form the best seed source. Seed from Morgan County, Tennessee, might also be satisfactory; this Tennessee source performed well both in our present study and in Aughanbaugh's *(1950)* study, which included 80 trees from each of six sources planted in Franklin County. Although Aughanbaugh's study did not include planted trees of a local source, he did state that native Franklin County shortleaf pines grew much faster than trees from out-of-state sources.

Local seed should be used in establishing loblolly pine stands in Maryland and shortleaf pine stands in southern New Jersey or southeastern Pennsylvania. Local sources provide trees adapted to the local climates, and these trees usually grow much faster in the Northeast than stems that originate from seed collected farther south.

In Pennsylvania, only experimental plantings of shortleaf pine seem advisable in the Ridge and Valley Province, and these should be restricted to apparently favorable site and climatic conditions. More extensive plantings of shortleaf pine should be limited to areas southeast of that province, and mostly to the southernmost counties.

LITERATURE CITED

Aughanbaugh, J. E.
1950. SHORTLEAF PINE IN SOUTHERN PENNSYLVANIA. Pa. Forests and Waters 2: 82-85, 93, illus.

Coile, T. S., and F. X. Schumacher.
1953. SITE INDEX OF YOUNG STANDS OF LOBLOLLY AND SHORTLEAF PINES IN THE PIEDMONT PLATEAU REGION. J. Forestry 51: 432-435, illus.

Fowells, H. A.
1965. SILVICS OF FOREST TREES OF THE UNITED STATES. U. S. Dep. Agr. Agr. Handbook 271. 762 pp., illus.

Little S., and H. A. Somes.
1964. LOCAL SOURCES OF LOBLOLLY PINE IN MARYLAND AND SHORTLEAF PINE IN NEW JERSEY OUTGROW SOUTHERN STOCKS. USDA Forest Serv. Tree Planters' Notes 67: 18-19, illus.

Perry, George S.
1924. DISTRIBUTION OF SHORTLEAF PINE IN PENNSYLVANIA. Forest Leaves 19: 134-135.

Shafer, Elwood L., Jr., and Henry H. Chisman.
1957. THE NORTHERN EXTENT OF SHORTLEAF PINE IN PENNSYLVANIA. Pa. Forests 37: 10-11, illus.

Wells, Osborn O., and Philip C. Wakeley.
1966. GEOGRAPHIC VARIATION IN SURVIVAL, GROWTH, AND FUSIFORM-RUST INFECTION OF PLANTED LOBLOLLY PINE. Forest Sci. Monogr. 11. 40 pp., illus.

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SEED LOSSES

to Small Mammals after Fall Sowing of Pine Seed

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
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SEED LOSSES to Small Mammals after Fall Sowing of Pine Seed

TO PROTECT PINE SEEDS

WHEN endrin and arasan came into use about 10 years ago as protective seed coatings, foresters believed they had an answer to the main problem in direct-seeding pine—how to keep rodents and birds from eating the seed. Though early trials were encouraging, recent reports have indicated that the chemical coating does not always give the seeds adequate protection (*Graber 1965, Langdon and Legrande 1965, Radvanyi 1966*).

So we made a study under field conditions to determine whether the degree of protection could be improved by increasing the endrin concentration in the seed coating. We found that, when the seeds were sown on the soil surface, seed losses due to small mammals were still severe—regardless of endrin concentration. The best results were obtained by covering the coated seeds with soil at planting time.

THE STUDY

This study was designed as a split-split-plot experiment. Three replications were established in burned-over scrub hardwood stands in southwestern Maine (table 1). Each main plot consisted of 6 furrows 12 feet apart and 132 feet long, plowed with a fireline plow. The 4 main plots in each replication were separated by at least 130 feet to minimize small mammal travel between plots. Each main plot was divided into two seed-ex-

Table 1.—Dominant vegetation and soils of the experimental areas

Replication	Dominant vegetation	Mean d.b.h.	Mean height	Stems per acre	Basal area per acre	Age	Origin	Soil series and type
		In.	*Ft.*	*No.*	*Sq. ft.*	*Years*		
Area I	Black oak, *Quercus velutina* Lam. White oak, *Q. alba* L.	2.5	20.0	889	30.84	18	Sprouting after fire	Windsor loamy sand
Area II	Black oak Gray birch, *Betula populifolia* Marsh Paper birch, *B. papyrifera* Marsh.	2.8	22.6	913	39.24	18	Seed and sprouting after fire	Charlton loam
Area III	Quaking aspen, *Populus tremuloides* Michx.	1.2	13.8	2,723	20.15	8	Sprouting after fire	Ninigret sandy loam

posure sub-plots, and each sub-plot was further subdivided into two sub-sub-plots to test differences between species. Treatments were assigned randomly at all levels.

We recognized that seed size and seed exposure might influence the effectiveness of the protective coating. So as part of our study, we used the small red pine (*Pinus resinosa* Ait.) seeds and the larger white pine (*P. strobus* L.) seeds to see if seed size influences depredation. We also compared two levels of seed exposure to see if seeds sown on the surface were more vulnerable to rodent depredation than seeds buried in the soil. The relatively large white pine seeds (28,000 per pound) were buried 1/3 inch deep and the smaller red pine seeds (53,400 per pound) were buried 1/4 inch deep. The surface exposure treatment consisted of simply dropping the seeds on the mineral soil seedbed.

The Protective Coating

We used Spencer's (*1959*) method to apply the protective seed coating. The endrin,[1] arasan,[2] and latex sticker were mixed together; then the seeds were tumbled in the mixture until they were coated.

Four endrin concentrations were used: 1/2 percent, the concentration recommended by Spencer; 1 percent, as suggested by Derr and Mann (*1959*) and later by Kverno (*1964*) where populations of seed predators were high; 2 percent, the concentration proved superior in our small-scale laboratory feeding trials with small mammals; and 4 percent, which is considered the practical maximum usable in a field experiment of this kind. The percentage of active endrin was based on the oven-dry weight of the seed to be treated.

The bird repellent, arasan, was applied at a rate of 1.5 percent effective ingredients per unit seed (oven-dry) weight. While the protective coating was still moist, the seeds were over-coated with aluminum powder.

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[1] Hexachloroepoxyoctahydro-endo-endo-dimethanonaphthalene. Source: Endrin 50W.

[2] Tetramethyl thiuram disulphide. Source: Arasan 75.

Seeding

Coated seeds of high viability (white pine 95.6 percent, red pine 98.0 percent) were planted in early November 1964. Seeds either were dropped on the surface or were buried in a small hole of appropriate depth. The seed spots were established in the center of the furrow at 3-foot intervals. Each sub-sub-plot contained 60 seed spots sown with 5 seeds. Thirty of these seed spots in each sub-sub-plot were randomly selected and were marked with wire pins for observations of seed loss.

Observations of Seed Losses

The marked seed spots were inspected closely at weekly intervals during snow-free periods in the fall and spring after seeding. Three observations were made in November before a lasting snowcover. Weekly observations were resumed on 1 April and continued until June. Most of the remaining seeds had germinated by then.

The purpose of these observations was to determine the cause, amount, and time of seed losses. Seed losses were classified as: (1) *consumed by small mammals* when characteristic seed hull remnants remained; (2) *removed by small mammals* when seeds were missing from a seed spot where consumption by small mammals had just occurred; (3) *missing* when seeds could not be located and no evidence was found to link the loss with a specific predator; (4) *consumed by birds* when typical seed fragments remained; (5) *consumed by insects*; and (6) *miscellaneous*.

The frequent inspections of the marked seed spots, together with the high visibility of the aluminum-pigmented seedcoats, made possible a reliable record of seed losses.

Screened Plots

A series of screened plots was established at randomly chosen seed spots that had not been selected for observation in the main study. These plots were established only where the seed was sown on the surface. The individual seed spots were protected as follows: (1) *exclusion of all predators except insects* with a 1/4-inch mesh screen cone 6 inches in diameter at

the base: (2) *exclusion of birds and larger mammals* by an identical cone raised 1 inch off the ground to allow entry of small mammals; and (3) a *control* with no screen, completely open to all predators. Seventy-two of these single seed spot plots were established in each replication.

Small Mammal Census

A census of small mammals was made at 4-week intervals during the autumn and spring to follow population trends and species composition as related to the endrin concentration treatments. Fifty permanent live-trapping stations were established at each of the three replications. The stations were located on a 25-foot grid; 10 stations were on each of the 4 main plots, and 10 more were on an adjacent control plot where no seeding or site preparation had been done.

A Sherman live-trap baited with a rolled oats-peanut butter mixture and sliced apple was placed at each station. During the 5-day census periods, the traps were visited early each morning. Captured animals were examined, marked by toe clipping, and released. The resulting capture-recapture data were used as an index of small mammal activity on the study area.

RESULTS & DISCUSSION

Small Mammals

The first small mammal census was begun 15 October before site preparation and seeding operations, and the final census was completed 13 June. The peak catch occurred in the November trapping, with 130 captures. The number of captures in the December-May period averaged 73 per census. In June many juveniles entered the population, and the number of captures increased to 101. A total of 193 small mammals were captured 584 times from October to June.

By far the most important species in the small mammal population were the white-footed mice and red-backed voles (table 2). Together they accounted for 87 percent of the original captures and 100 percent of all recaptures. Both species

Table 2.—Species and number of small mammals captured during the seven 5-day census periods

Species	Animals captured	
	No.	*Percent*
White-footed mouse, *Peromyscus leucopus*	106	54.9
Red-backed vole, *Clethrionomys gapperi*	62	32.1
Masked shrew, *Sorex cinereus*	13	6.7
Short-tailed shrew, *Blarina brevicauda*	5	2.6
Eastern chipmunk, *Tamias striatus*	5	2.6
Red squirrel, *Tamiasciurus hudsonicus*	1	.5
Woodland jumping mouse, *Napaeozapus insignis*	1	.5
Total	193	100.0

are voracious consumers of pine seeds and were undoubtedly responsible for most of the seed losses that occurred in this study. The species of shrews found here feed largely on insects and other invertebrates and consume only small amounts of plant materials, including seeds (*Jackson 1961*). Since most of the shrews died in the trap (88 percent), they were virtually eliminated from the study area by the periodic trapping.

Chipmunks and red squirrels were captured or observed on areas I and II. The frequency of their capture is not indicative of numbers present in areas I and II because they were trap-shy, and none was ever recaptured. Only infrequently could seed fragments typical of their feeding be found, and it is believed that they had a minor effect on seed losses. This may be related to the good crop of oak mast that was produced on the two areas in the fall of 1964 and provided an abundant supply of their preferred food.

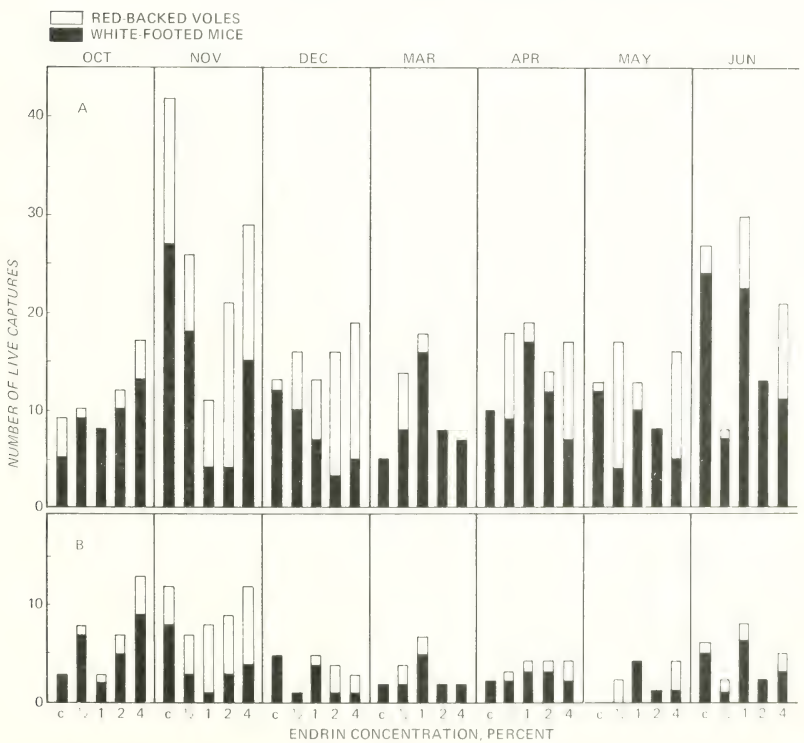
The small mammal populations were similar in number and species composition on the three replications except that there were no red squirrels or chipmunks on area III. The total number of small mammal captures and recaptures was 164 on area I, 201 on area II, and 219 on area III.

Effect of Endrin on Small Mammals

The four concentrations of endrin tested in the protective seed coatings appeared to have little effect on small mammal numbers or species composition.

A major possibility was that the small mammals living on or adjacent to the 2-percent and 4-percent endrin plots might suffer heavy mortality, and then the plots would be subject to reinvasion by animals from outlying areas. The animals most likely to show such a trend, if it did exist, were the white-footed mice and red-backed voles. The number of original captures and recaptures of these two species are shown in figure 1.

Figure 1.—Effect of endrin treatment on white-footed mouse and red-backed vole populations. The c (control) plots were not seeded. A, all captures, original plus recaptures. B, unmarked animals captured in each period.



No obvious decline in numbers or activity of the mice could be related to endrin concentration (fig. 1,A). A further measure of response to the protective seed coatings is the number of mice captured for the first time in each observation period (fig. 1,B). If the higher concentrations of endrin were causing mortality among mice, these plots would be invaded by animals from outlying areas, and the number of first-time captures on these plots would increase. This did not occur; heavy mortality due to endrin intoxication did not take place even at the highest endrin concentration. It appears that the effects of the higher levels of endrin in the protective coatings were minimal, lessening the possibility that the endrin concentrations tested here might cause significant injury to an existing small mammal population.

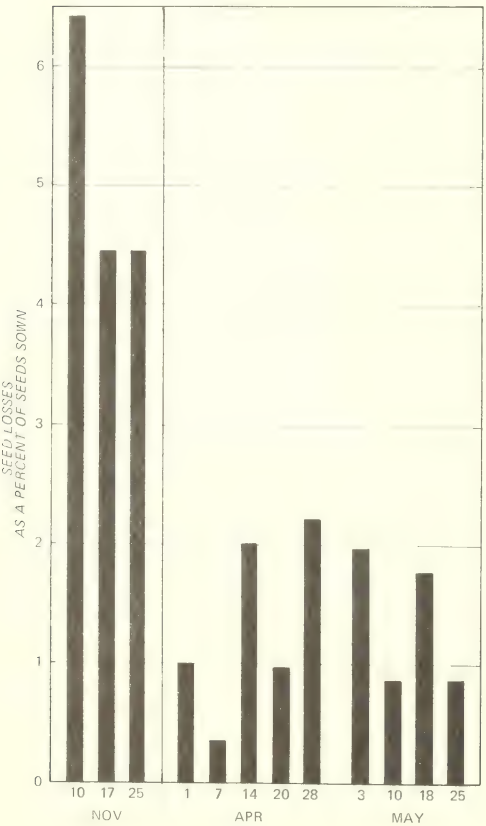


Figure 2.—Periodic seed losses from all causes during the dormant season (3 November to 25 May).

Time of Seed Losses

Heavy seed losses began immediately after sowing (fig. 2). At the end of the first week of exposure, 10 November, nearly 6 percent of the seeds on the observed seed spots had been destroyed. Fourteen percent of the seeds had been lost by the end of November, when a lasting snow cover made further observations impossible. In the spring the first weekly observation was made 1 April. Most of the losses observed at this time had occurred the previous fall between the time of the last observation, 25 November, and the first snowfall, which occurred 2 days later. This was apparent because of the weathered condition of the seed fragments. The level of seed losses increased erratically: peak spring losses occurred the last week of April and the first week of May. Total spring seed losses over the 9-week observation period were 12 percent. This indicates that maximum seed destruction may occur in the fall, and a lower level of seed destruction may occur over a much longer period in the spring.

Causes of Seed Loss

The major cause of seed loss was predation by small mammals (fig. 3). They consumed nearly one-half of all seeds lost. An additional one-third of all seeds lost were removed from seed spots where identifiable feeding had occurred. It was assumed that the animal responsible for the feeding had also removed the seed. Seed loss due to both consumption and removal by small mammals was 82 percent of the total seed loss.

Birds caused minor seed loss, approximately 1 percent of all losses. This most likely reflects the very small number of birds on the study area during late fall and early spring. Also, the arasan in the seed coating is a highly effective bird repellent.

No evidence of damage caused by insects was found. Loss due to miscellaneous factors, including trampling by deer, hunters, a dairy cow, and occasionally the observers was also minor. A final category was missing seeds, those that could not be located and where no concrete evidence could be discovered to link their disappearance with any other cause. However,

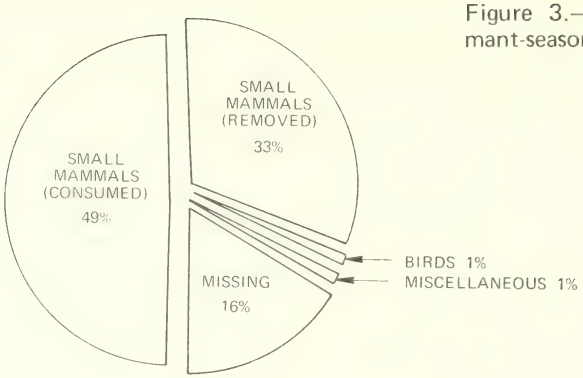


Figure 3.—Causes of dormant-season seed losses.

seeds in this category disappeared at a relatively constant rate, proportional to the seed loss caused by small mammals. It is probable that many of the missing seeds were in fact removed by these animals.

Seed Exposure

The experimental treatment having the greatest effect on seed loss was seed exposure. More than half of all seeds exposed on the surface were lost during the 7 months from 3 November to 25 May. Where the seeds were covered, less than 3 percent were lost.

At first it seemed strange that the small mammals did not discover and destroy more of the buried seed. Of the few covered seeds that were taken, almost every one had been lifted to the surface by frost action or soil washing. In very few places did it appear that an animal purposefully dug down to the seeds. Our hypothesis is that the covered seed, coated with protective chemicals, did not attract the attention of the seed-eating mammals. There can be no doubt that the animals present were capable of finding the seeds (*Howard and Cole 1967*). A possible explanation for their failure to do so is that the protective coating masked the odor of the seed or for some reason the odor was not associated with a known food source, even though coated seeds exposed on the surface nearby were being consumed.

Endrin Concentration

Because 95 percent of all seed losses occurred on the surface-sown plots, only they will be considered in this discussion. The effects of the endrin concentration treatment on seed losses were not statistically significant. This result appears to be due to the original study design, which provided a relatively insensitive test of the endrin concentration variable, and to the occurrence of a large within-treatment variation. However, an inspection of the data leads us to believe that real differences may exist (table 3). Certainly fewer seeds were lost at the 4-percent concentration than at the 1/2- or 1-percent concentration.

The influence of endrin concentration on the amount and time of seed loss is of particular interest (fig. 4). During the fall fewer than 10 percent of the surface-sown seeds coated with 4-percent endrin were destroyed while seed losses at the other concentrations ranged from 28 percent to 44 percent. In the spring the trend changed. Seed losses in the 4-percent endrin treatment exceeded all but those in the 1/2-percent treatment.

To some degree this increased proportion of seed loss in the most severe endrin treatment may simply reflect seed availability. Many more 4-percent endrin-coated seeds were exposed in the spring because much higher percentages of the seeds in the other endrin treatments had been destroyed in the fall. It is logical to assume that the small mammals responsible for over

Table 3.—Total number of seeds lost during the dormant season
(Seeds exposed on the surface)

Replication	Endrin concentration				
	1/2%	1%	2%	4%	Σ
I	68	190	107	58	423
II	209	122	147	63	541
III	273	265	186	162	886
Σ	550	577	440	283	1,850

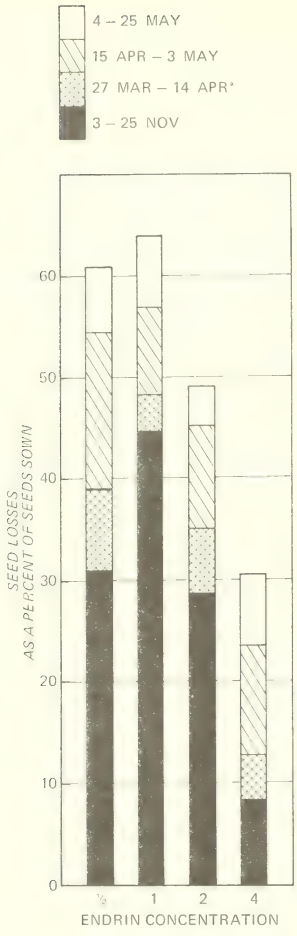


Figure 4.—The influence of endrin concentration on seed losses from 3 November to 25 May. (Seeds exposed on surface.)

*Seed losses occurring after 25 November and before a lasting snow cover 2 days later are included here.

82 percent of the seed loss consumed and removed the seeds treated with the lowest endrin concentrations first; and in the spring, when the low-endrin concentration seeds were relatively scarce, they destroyed larger amounts of the high-endrin seed.

Weathering of the protective coating would also tend to reduce differences among the endrin treatments. By spring the coating had visibly deteriorated; large flecks of the coating had sloughed off the seeds exposed on the soil surface.

A visual estimate of the loss of protective seed coating was made in late May. The average coating loss was approximately

Table 4.—Number of seeds lost to small mammals
(Seed exposed on the surface)

Endrin concentration (percent)	Consumed	Removed	Total	Consumed/removed ratio
1/2	242	253	495	0.94
1	237	230	467	1.03
2	220	136	356	1.62
4	129	61	190	2.11

40 percent; loss ranged from 0 to 100 percent. This loss of coating undoubtedly reduced the effectiveness of the endrin treatment and was a factor in the high spring losses of seeds coated with 4-percent endrin.

Endrin concentration had an effect on the proportion of seeds consumed to seeds removed (table 4). Where seeds were coated with 1/2-percent endrin, small mammals removed slightly more seeds than they consumed. At the highest endrin concentration, more than two seeds were consumed for each seed removed.

Consumption and then removal of some or all of the remaining seeds, presumably to a cache, reflects a higher degree of small mammal acceptance than consumption alone. That is, animals that consumed seeds treated with the higher endrin concentration may have been so repelled by the protective coating that relatively few seeds were removed for storage.

Effect on Species

White pine seed loss, although greater, was not significantly different from red pine seed loss. Where the seeds were exposed on the surface, 58 percent of the white pine seeds were lost and 45 percent of the red pine seeds were lost. These differences reflect mainly what appears to be selective feeding by small mammals in November when 32 percent of the white pine seeds were destroyed compared to 23 percent of the red pine seeds.

In the spring, seed losses were nearly identical for the two species.

Screened Seed Spots

The protection afforded by the conical screen covers had a major effect on seed losses. When the base of the cone was in firm contact with the soil, excluding all seed predators but insects, only 3.6 percent of the seeds were lost. In no case were any seed fragments found linking this loss with any predator, including insects; the seeds simply vanished. Most likely soil disturbance caused by frost heaving and rain washing was responsible for this seed disappearance. Most of these losses occurred during relatively cold portions of the dormant season when the soil was freezing nightly—a time when little insect activity would be expected.

Where the screen cones were raised 1 inch (open-cone), allowing the entry of small mammals, losses were surprisingly light; only 27.5 percent of the seeds were lost. The proportions of seed loss caused by each agency was almost identical to those in the main study (fig. 2), except that no seeds were taken by birds.

The unprotected seed spots suffered the heaviest loss (61 percent), exceeding by nearly 10 percent the loss that occurred on the main study under similar conditions. However, the proportion of seed loss caused by each agency was very similar to that in the main experiment. Small mammals were responsible for 85 percent of all losses on the unprotected seed spots and a similar proportion (82 percent) in the open-cone seed spots. The large difference in total seed losses between the open-cone and the unprotected seed spots may indicate that the small mammals were reluctant to enter the open cones. Another observation that supports this hypothesis is that nearly 60 percent of the seeds destroyed by small mammals were consumed on the unprotected seed spots, but only 44 percent of those destroyed on open-cone spots were consumed there. The rest were removed, presumably to the protective cover of the adjacent familiar habitat.

CONCLUSION

Heavy seed losses caused by small mammals, primarily white-footed mice and red-backed voles, occurred wherever seeds treated with the recommended concentrations of endrin (1/2 and 1 percent) were exposed on a mineral seedbed. An increase in the endrin concentration of the seed coating appeared to reduce losses, but the reduction was not statistically significant.

Birds caused only minor seed losses. Because birds are the major seed predators in the South, this result may be surprising. However, the migratory birds were gone before sowing in the fall and did not return until just before germination in the spring. And, arasan, which was a component of the protective seed coating, is an effective bird repellent.

The time of seed loss is particularly interesting. More than half of all seed losses occurred during the 3 weeks in the fall after sowing and before a lasting snow cover. This result is no doubt related closely to the large number of small mammals present at this time. A logical conclusion is that fall sowing should be avoided, especially when small mammals are abundant and the seeds are to be left exposed on the seedbed surface.

When given a clear choice, the seed predators might select the larger white pine seeds in preference to red pine seeds. But the differences between the two species were not significant statistically and are not likely to be of practical importance because both species were readily accepted by the predators. For both species, the amount of seeds destroyed was great where seeds were sown on the surface and exceeded a level that could be readily tolerated in practical regeneration operations.

The most important observation of this study was that very few seeds were lost when the seeds were covered with soil; and more than half of the seeds sown on the surface were destroyed—primarily by small mammals. This means that methods of direct seeding that cover the seeds are much more efficient than broadcast methods. This is especially so where seed is scarce or expensive. In the past, seeds that had to be

covered with soil were sown by hand because the rough, stony, wooded land so typical of New England prevented the use of machinery. And hand sowing was almost prohibitively expensive. But a recently developed mechanized seeder (*Graber and Thompson 1967*) sows and covers the seeds efficiently, providing a practical application of this finding.

Literature Cited

Derr, H. J., and W. F. Mann, Jr. 1959. GUIDELINES FOR DIRECT-SEEDING LONGLEAF PINE. U.S. Forest Serv. S. Forest Exp. Sta. Occas. Paper 171, 22 pp.

Graber, R. E. 1965. DIRECT SEEDING WHITE PINE IN FURROWS. IN PROC. DIRECT SEEDING IN THE NORTHEAST—A SYMPOSIUM. Univ. Mass. Exp. Sta. Bull.: 99-101.

Graber, R. E., and D. F. Thompson. 1967. MECHANIZED DIRECT SEEDING—A FURROW SEEDER FOR ROUGH, STONY LAND. S. Lumberman 215 (2680): 122-123.

Howard, W. E., and R. E. Cole. 1967. OLFACTION IN SEED DETECTION BY DEER MICE. J. Mamm. 48: 147-150.

Jackson, H. H. T. 1961. MAMMALS OF WISCONSIN. 504 pp., illus. Univ. Wis. Press, Madison.

Kverno, N. B. 1964. FOREST ANIMAL DAMAGE CONTROL. 2nd Vertebrate Pest Contr. Conf. Proc. 2: 81-89. Anaheim, Calif.

Langdon, O. G., and W. P. Legrande. 1965. RODENT DEPREDATION—A DIRECT SEEDING PROBLEM. U.S. Forest Serv. Res. Note SE-39. 2 pp. SE. Forest Exp. Sta., Asheville, N. C.

Radvanyi, A. 1966. DESTRUCTION OF RADIO-TAGGED SEEDS OF WHITE SPRUCE BY SMALL MAMMALS DURING SUMMER MONTHS. Forest Sci. 12: 307-315.

Spencer, D. A. 1959. A FORMULATION FOR THE PROTECTION OF SEED FROM ANIMAL DAMAGE. Wildlife Res. Lab. Bur. Sport Fish. and Wildlife Mimeo. 4 pp. Denver, Colorado.

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SAPSUCKER

Damage Varies with Tree Species and Seasons

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by Francis M. Rushmore

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NORTHEASTERN FOREST EXPERIMENT STATION, UPPER DARBY, PA.
FOREST SERVICE, U. S. DEPARTMENT OF AGRICULTURE
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Figure 1.—This 9-inch paper birch was killed by sapsuckers during the second year of feeding.

SAPSUCKER

Damage Varies with Tree Species and Seasons

A Growing Concern About the Sapsucker

AS USE of our forests intensifies, we foresters are paying more and more attention to the agents that damage trees. Much attention has been paid to fire, insects, and diseases. Now we are becoming more concerned about the damage done by animals and birds.

One bird that draws our attention is the yellow-bellied sapsucker. This sapsucker (*Sphyrapicus varius varius* L.) is a member of the American woodpecker family. It attacks trees to feed on the sap and bark tissues (fig. 1). Its attacks can kill the tree or seriously degrade the wood.

To learn more about this bird, the damage it does, its habitat, and its ecology, the Northeastern Forest Experiment Station has made a 5-year series of observational studies of this sapsucker and its behavior and feeding habits in our New England forests.

IMPORTANCE

Ornithologists—whose concern has been mainly with the bird itself—reported more than 100 years ago that the sapsucker attacks orchards, shade trees, and forest trees. A few studies, beginning about 60 years ago, have directed attention to the damage done to forest trees.

Our best information dates back to 1911, when McAtee (*4*) described different kinds of sapsucker damage and summarized what was then known about the sapsucker in the United States. Much of his information was based on studies south of the bird's nesting range. He estimated that sapsuckers damaged at least 10 percent of the trees within their range, and in some areas more than 90 percent of the trees. He reported damage to the wood of 174 tree species.

We can only guess how widespread sapsucker damage is today. But we are beginning to acquire up-to-date information. For example, in 1968 the U.S. Forest Service included evaluations of sapsucker damage among the data to be collected in its forest survey of Maine—the first state-wide survey of sapsucker damage.

Sapsuckers not only injure the tree; they also damage the wood. One common kind of damage attributed to sapsucker attack is known as bird peck. Another is the discoloration associated with sapsucker wounds. The literature cited refers to other kinds of damage.

RANGE

Of the four subspecies of yellow-bellied sapsucker, only one—*Sphyrapicus varius varius* L.—occurs in eastern North America (*2*).

This sapsucker is a migratory bird. It spends the summers on its northern nesting range in the United States and Canada. This range extends from the East Coast nearly to the West Coast, generally between 40 and 50°N. latitude in the East and 52 to 63°N. in the Pacific Northwest. The range also extends southward along the Appalachian Mountains to about 35°N. (*2*).

This sapsucker's winter range is generally south of 40°N. and as far south as the West Indies and Central America.

Because of this wide migratory range, the sapsucker may attack trees throughout most of North America. At some time of the year this sapsucker or the three western subspecies can be found in all the timber-producing regions of North America.

In New England, sapsuckers can be found on their nesting range from about mid-April till late September or early October. Throughout that period their major foods are tree sap and bark, and insects.

Study Methods

Our study was designed to find when and how sapsuckers damage trees in this region, and whether they prefer some tree species to others.

Observations for this study were made during five summers, 1964 to 1968. Most of the work was done on our 4,000-acre Penobscot Experimental Forest near Orono, Maine. Some observations were made in other parts of eastern Maine, in northern Pennsylvania, in the Adirondack Mountains of New York, and in New Brunswick and Nova Scotia, Canada.

Ninety-two percent of the observations that were made within sapsucker territories and along a 5-mile sapsucker survey route were made by the observer traveling on foot. Travel on this route totaled 137 miles. The other 8 percent of the observations were made after approaching known feeding trees in an automobile.

Most observations were made at a distance of less than 100 feet. Binoculars were used (7 x 50 or 8.5 x 44).

A bird was considered to be feeding only if its drilling on the tree was intensive enough to produce substantial amounts of sap or bark. Casual pecking around old sapsucker holes was not counted as feeding.

Identifying the sapsucker territory is extremely important in the study of this bird and the damage it does. Sapsuckers establish strong nesting and feeding territories in woodlands during the spring, and stay there until fall. In the spring only

one pair will occupy a territory. Later in the summer and fall a family of about six birds (including offspring) will occupy the same territory. They do not move haphazardly about the forest. This permitted intensive study of the birds.

Twenty-seven sapsucker territories were delineated on the Penobscot Experimental Forest. These provided 96 percent of the observations (table 1).

Table 1.– Number of tree-days[1] sapsuckers were observed feeding, April 1964 through October 1968

Species	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Eastern hemlock	32	45	2	3	14	20	–	116
Red spruce	15	21	1	3	2	3	2	47
Black spruce	2	–	–	–	1	–	–	3
White spruce	–	–	–	–	1	–	–	1
Balsam fir	–	–	6	2	1	2	1	12
Eastern white pine	–	–	–	–	2	2	1	5
Northern white-cedar	1	–	–	1	2	2	–	6
Tamarack	–	–	–	–	2	–	–	2
Quaking aspen	13	4	2	–	1	7	–	27
Bigtooth aspen	2	1	–	–	–	–	–	3
Red maple	6	51	22	22	25	45	6	177
Sugar maple	–	2	2	3	3	–	–	10
Striped maple	1	–	–	–	–	–	–	1
Silver maple	–	–	–	–	2	–	–	2
Paper birch	3	23	28	70	75	133	34	366
Gray birch	–	5	6	14	10	9	–	44
Yellow birch	–	1	–	3	4	–	–	8
Northern red oak	–	4	1	3	1	5	4	18
American beech	–	1	–	–	–	3	1	5
Serviceberry	–	1	–	–	2	2	7	12
American elm	–	1	1	1	–	1	3	7
Elm (exotic)	–	–	–	–	2	–	–	2
Speckled alder	–	–	–	6	–	–	–	6
Red berried elder[2]	–	–	–	2	–	–	–	2
White ash	–	–	–	1	2	3	1	7
Black ash	–	–	–	1	–	1	–	2
Eastern hophornbeam	–	–	–	–	–	–	2	2
Apple	–	1	–	–	–	4	1	6
Total	75	161	71	135	152	242	63	899

[1] One tree-day: feeding was counted only once per day, regardless of number of times observed or the number of birds feeding on the tree.

[2] Fruit eaten.

The other 4 percent of the observations were obtained in 49 additional territories: 2 percent were made on other parts of the Experimental Forest; 1 percent were made elsewhere in eastern Maine; 1 percent were made in northern Pennsylvania, the Adirondack Mountains of New York, and in New Brunswick and Nova Scotia, Canada.

Sapsuckers used 47 percent of the Experimental Forest. This was determined by a 12-percent survey of the 4,000 acres in 1966. The 27 territories averaged 7.6 acres. These same territories were occupied for at least three summers (1966-68), and probably for many years before that.

The 27 territories were found by using a new sapsucker calling and surveying technique (*F. M. Rushmore, publication pending*). It was from 5 to 11 times more efficient than birding techniques commonly used (*7*).

An important element of this technique is the distinctive drumming used by sapsuckers. It can be used to identify sapsuckers without seeing them. Most drumming occurs in spring. No other woodpecker in this region drums the same way. And as far as I know, no other woodpecker in any region does it the same way, except other sapsuckers (*2*). The first part of the sapsucker's drumming is a fairly rapid beat (it is generally similar to the complete drumming of other kinds of woodpeckers). Only the sapsucker has the special ending of several more slow, measured taps. A whole sequence might go about like this: . . . . . — — — — —

On a calm day this can be heard at least 600 feet.

When sapsuckers were observed feeding, these data were recorded: tree species and d.b.h. of trees; area location; bird age and sex; date and time; and other related data. To be included in this report a sapsucker must have been seen actually drilling or feeding on a tree. The only exceptions (1 percent of the 899 observations) were when birds were not present, but daily inspection of trees definitely identified new sapsucker holes.

To obtain the 899 observations (table 1), 535 trees were counted no more than once per day, regardless of the number of times birds were observed feeding. Feeding was observed on

205 days, on 26 tree species and 2 shrub species. Sapsuckers were under observation 650 hours. An estimated 714 sapsuckers occupied the areas when observations were made.

From 1964 to 1968, in consecutive order, the earliest spring observations of sapsuckers on the Experimental Forest were made on 17, 30, 20, 25, and 19 April; the last fall observations were made on 30 September, 7 October, 29 September, 13 October, and 5 October. These dates do not necessarily mean first arrival or last departure.

Results

The sapsuckers showed seasonal preferences among the species they were seen feeding on (table 1). In early spring they fed on hemlock, spruce, and aspen for several weeks. Then they used red maple heavily in May and at least until mid-June. By late May the three birch species had assumed increasing importance, which continued throughout the summer. In dry years, apparent moisture stress in birch and other hardwoods drove the sapsuckers back to the hemlocks. Some other tree species provided important food in the fall.

FEEDING HABITS

The sapsuckers had feeding habits that made repeated observations easy. The same birds made frequent trips to the same tree daily. These visits continued for periods lasting several days to several months. Sapsuckers drilled only on live trees to get sap and bark. It was easier to identify sap feeding than bark feeding.

Sap.—Feeding on sap was recorded when these clues were apparent:

- A bird's visit to a number of existing fresh holes, and sap-collection activities not accompanied by drilling.
- Definite rapid siphoning of sap from holes—where sap had filled the holes and its removal could be clearly seen.
- Wet sap on the tip of a bill.

- Insertion of the bill tip at the bottom of sap holes and moving it from one side to the other, to wipe up, or to siphon, small quantities of sap.

When sap occurred in very small quantities, I could not always tell definitely whether the bird was feeding on sap, phloem, or other tissues.

My observations gave substantial evidence of sap feeding on 14 of 19 species observed in 1964. And by 1968 sap feeding had been observed on 23 of the 28 species listed in table 1: the exceptions were white spruce, tamarack, beech, hophornbeam, and elder. Sap feeding probably occurred on all species except elder, but there were too few observations to establish this definitely.

It has been reported that sapsuckers get intoxicated by feeding on fermented sap or fruit. I did not see any evidence of intoxication. Sapsuckers normally avoided fermented sap and fed only on fresh sap. Among the 532 birds I saw feeding on sap, only on two occasions did I see birds take fermented sap. One juvenile bird tasted it and went immediately to fresh sap. Another time, a pair of adults fed their fledglings on solidified fermented paper birch sap. The evidence suggests that this probably was necessary because red squirrels (*Tamiasciurus hudsonicus loquax* Bangs), feeding only on fresh sap, denied the birds access to their own sap holes.

Woody tissues.—Feeding on live bark tissues was common. I often saw small bits of it being eaten. I assumed that it was phloem, but specimens were not taken from the birds for identification. I do not know of any report that cites precise identification of the bark tissues sapsuckers eat.

A different kind of feeding occurred near the cambium, on what I assumed to be new callus tissues. It occurs around the perimeter of the sap pits. Specimens were not taken for examination. This kind of feeding is common and distinctive. The very rapid taps with the bill are noticeably faster than those used for other bark feeding or drilling.

None of the holes I saw extended noticeably into the xylem. A few of the soft outer cells might be eaten.

Drying of the xylem and bark at the holes is a serious matter. Once dead, the xylem does not join again on that plane, even if new wood eventually covers it. Some effects of that have been described (*3, 4, 9*).

Insects.—Insects were a major food of sapsuckers. My 1,301 recorded observations of insect feeding do not represent the total observed. Sapsuckers were experts at catching insects in mid-air. But they accepted other opportunities in virtually any location. Insects made up the bulk of the nestlings' food. Adult birds generally added sap to a bill full of insects just before flying to the nest. To a lesser extent, insects were fed without the sap.

TREE MORTALITY

Many of the birds' favorite hardwood trees probably will be killed by repeated drilling within future years—assuming that the sapsucker population remains fairly constant. Here is the tree mortality that sapsuckers had already produced among all damaged trees found within ten nesting territories in 1964:

Species	*Trees damaged (number)*	*Mortality*[1] *(percent)*
Red maple	190	40
Paper birch	102	51
Gray birch	39	67
Hemlock	73	1
Red spruce	31	3
Total	435	—

[1] *Trees dead or nearly dead.*

Intensive feeding can kill a small tree in a single season, but generally two or more years of drilling are needed to kill trees 8 inches d.b.h. or larger.

DAMAGE IN LIVING TREES

Sapsucker damage was found on 51 species. Feeding was actually observed on 28 species (table 1). The other species, on which only damage was observed, were:

Wild apple	Boxelder
Crab apple	American mountain-ash
American basswood	Black oak
White birch (2 horticultural species)	White oak
Buckthorn	Scotch pine
Black cherry	Red pine
Chokecherry	Balsam poplar
Pin cherry	Lombardy poplar
Hawthorn	Staghorn sumac
American hornbeam	Willow (3 species)

The conifers and the less-favored hardwoods may continue to receive some damage annually, but most of them probably will live. This is based upon the assumption that drastic changes will not occur in either the stand compostion or the sapsucker population.

The quality of the wood in these living trees will depend upon the frequency and severity of the damage. Ring shake and other quality-reducing internal defects in trees remaining alive after being damaged by sapsuckers have been described elsewhere (*3, 4, 8, 9*). Bird peck defect caused by sapsuckers has been discussed in numerous publications. Many of our living trees will contain the same kinds of defects.

Other damaged trees may heal and escape further damage for an unpredictable number of years—provided they are not used by subsequent sapsucker populations. Damaged wood fibers will remain within the trees and reduce the wood quality. Some trees may escape further damage for many years, and then may be revisited by sapsuckers and may be killed in one summer by intensive feeding.

Conifers

Hemlock.—Eastern hemlock (*Tsuga canadensis* (L.) Carr) was the conifer that sapsuckers fed on most in this area (table 1). Repeated annual sapsucker attacks on hemlocks are common in this region. Both local and migrant birds are responsible.

This feeding on hemlocks was seasonal: it was not continuous throughout the growing season. Most feeding on hemlock occurred upon arrival of the birds about mid-April and continued into May. This period overlaps with early concurrent

feeding on red spruce and later heavy feeding on paper birch and red maple in May.

Droughts apparently affected the feeding pattern. Sapsuckers fed heavily on hemlocks in spring 1964, switched to hardwoods, and then resumed feeding on hemlocks to a lesser extent later in the summer—after the sap in hardwood species diminished. Essentially the same sequence occurred in 1968, when severe moisture stress apparently occurred in paper birch and red maple about the last week of August, and the birds had to feed on hemlocks. Within 2 weeks, and after rains, sapsuckers had abandoned the hemlocks and returned to the paper birches.

When droughts did not occur, sapsuckers seldom fed on hemlocks in summer. With adequate rainfall in July 1966, and an abnormal abundance in the summer of 1967, sapsuckers used hemlocks very little in those summers. Juvenile birds did a little casual drilling late in those summers, but the adults retained possession of their favorite paper birches.

Red spruce.—Sapsucker work on red spruce (*Picea rubens* Sarg.) occurred mostly during late April and early May, about the same time as on hemlock (table 1). The only drilling observed on red spruce after 11 May, 1964 was done by two juvenile birds, one on 16 July and one on 14 August. A similar pattern occurred in the other years.

Other conifers.—The sapsuckers showed little interest in black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill.), northern white-cedar (*Thuja occidentalis* L.), and eastern white pine (*Pinus strobus* L.) within the stands under observation (table 1). Most of the summer drilling on these conifers seemed to be casual exploration by juvenile birds.

Hardwoods

Birches.—The birches were the favorite trees of sapsuckers. Paper birches (*Betula papyrifera* Marsh.), most abundant in the stands, were used heavily. Few yellow birches (*B. alleghaniensis* Britton) were available, but most of those found had been killed or damaged by sapsuckers. Gray birch (*B. populifolia* Marsh.) was used more than the data indicate. Damage found on gray birches was not always useable because birds were absent. In

several areas gray birches seemed to be preferred over nearby paper birches.

Data were inadequate for comparing relative preferences for the three birches.

Paper birch.—Among all the trees available, paper birch appeared to be the favorite species. It normally was fed upon from April to October (table 1). Paper birches that earlier in summer had served as major sources of food for adults and nestlings were closely guarded later by adult birds, from late July until the migration began in late September or early October.

Paper birch remained the favorite species of sapsuckers even in August and September 1964 and 1968 when drought conditions appeared to diminish sap flow drastically, compared with earlier in the summer. Moisture stress in the birches as appeared to force sapsuckers to work on hemlocks in both years. They returned to birch later. Adult birds continued to guard their favorite band of holes and appeared to feed more heavily upon the birch bark. Bark was removed between vertical rows of holes, thus enlarging them into abnormally wide and long strips (0.5 inch to about 1.25 inch wide, and up to several inches long) (fig. 1).

Although most holes were drilled on birch trunks, holes also were made on branches. Drilling on branches happened mostly in spring. The birds also commonly drilled substantial numbers of holes on birch branches in late summer, when their preferred holes on the trunk no longer produced sap. Improved sap production after heavy rains brought birds back to the trunk, except on trees rapidly dying from sapsucker damage.

Red maple.—Red maples (*Acer rubrum* var. *rubrum* L.) were used heavily by sapsuckers in spring of all 5 years (table 1). But in summer use varied widely and appeared to depend upon the amount of rain. After 25 June, 1964, use had noticeably lessened, about half the time consisting of casual drilling around old holes by juvenile birds. During the exceptionally dry summers of 1964 and 1968, red maples were used for casual drilling by both juveniles and adults while they awaited a turn at the sap holes on a favorite birch. But such feeding was of

short duration and few fresh holes appeared on red maples during July and later. The last sap feeding on red maple in 1964 was observed on 8 June. It appeared that feeding on bark tissues, rather than sap, occurred from July on.

The abnormally wet summer of 1967 produced a marked difference in sapsucker use of red maples, as compared with the drought summer of 1964. In 1967 some red maples produced sap throughout the summer and were used into October. Even when that happened paper birches were more favored (table 1).

In relatively dry summers some red maples on the edge of marshy ground were used more and longer than nearby red maples on higher, drier ground. However, in general, these sapsuckers began leaving hemlocks and spruces and turning gradually to intensive feeding on red maples in early May, and this continued until about mid-June. By then the birds had become more interested in the three birch species. There was no sharp demarcation in use of different tree species: it was a gradual process, with considerable overlapping.

Sugar maple.--Only a few sugar maples (*Acer saccharum* Marsh.) occurred in the territories studied. On 18 June, 1964 strong flows of sap occurred at sapsucker holes on a 7-inch d.b.h. sugar maple and on a nearby 11-inch paper birch on our Maine forest. These trees served as major sources of sap for a pair of sapsuckers feeding nestlings. The same sapsucker activities occurred on 30 June, 1966 on a 12-inch sugar maple in northwestern Elk County, Pennsylvania.

Aspens.--Neither of the aspen species appeared to be favorite trees for sapsucker feeding except in late April, when sapsuckers commonly fed on sap from the branches of quaking aspen (*Populus tremuloides* Michx.) and bigtooth aspen (*P. grandidentata* Michx.) (table 1). The holes were made within 3 to 5 feet of the branch tips.

Aspens here normally are not used as much by sapsuckers as birch or maple. Sapsuckers fed lightly on the boles of the largest aspens. I found small quaking aspens damaged on clearcut strips. The smallest quaking aspen I have found with sapsucker holes was 1-3/4 inches d.b.h. It appeared that aspen here was used more when other preferred species were not available.

However, aspens are favorite sapsucker nesting trees in this area. Of the 29 nests found in 1964, 25 were in aspens.

Red oak.—Sapsuckers fed on northern red oak (*Quercus rubra* L.) more than is indicated by table 1. Other evidence of heavy feeding was found when the birds were not present. Few oaks occur in the stands where these observations were made.

When moisture stress increased in paper birch, resident sapsuckers frequently fed on red oaks available within their territory. This occurred with increasing frequency in September. It was continued by migrants into October.

Sapsuckers killed one or two northern red oak limbs about 5 inches diameter on several trees on the Penobscot Experimental Forest. But that is not common here because the birds prefer paper birch, and the supply is ample. Local birds and migrants do not feed on many of the oaks here long enough to form the large bands of holes necessary to kill the stems.

I do not know for sure that oaks become favorite trees as the birds proceed south. But the limited evidence available suggests that northern red oak and other oaks may be major species for sapsucker feeding during their fall migration. Other kinds of oaks observed in Massachusetts and Connecticut appear to have been damaged by fall migrants.

In any region where oaks are a favorite species, and sapsuckers stay long enough to make many holes in individual trees, greater damage probably would result than occurs here. Oaks are damaged on the migratory and wintering ranges south of here (*4*).

Ash.—Neither white ash (*Fraxinus americana* L.) nor black ash (*F. nigra* Marsh.) were fed on very much by sapsuckers in this area (table 1). Only juvenile birds were seen drilling white ash in 1964. An adult that I disturbed near its nest drilled one hole in a black ash; this appeared to be a diversionary action, rather than feeding. Intensive feeding does occur on a few ash here in early fall, but it is rare—compared with feeding on most other hardwoods.

Another common practice is light tapping and wiping that appears more to involve bill cleaning than feeding. Loafing and preening occur at the same places. I have seen this repeatedly on

individual ash and northern white-cedar. It also occurred on the edges of dead bark on other species. This should not be misinterpreted as feeding.

Other hardwoods.—Serviceberry (*Amelanchier laevis* Wieg.) was used mostly in the fall (table 1). The birds paid it little attention until birch sap became scarce.

In the fall of 1967 and 1968, the same 8-inch d.b.h. serviceberry was used heavily by local birds and by migrants as late as 13 October, 1967. In early October 1967 profuse quantities of sap flowed, diminishing rapidly as the foliage colored. Sap flow in 1968 was noticeably less, perhaps because of the summer drought.

Is serviceberry a favorite species of fall migrants? It may be if it consistently produces sap later than other hardwoods along the migration route, as it has here. The literature does not provide an answer.

Striped maple (*Acer pensylvanicum* L.) generally is a small tree in this region. I observed feeding on it only once, in April. A few other damaged trees were found when birds were not present. It appeared to be low on the preference list when other and larger hardwoods were available.

Other hardwood species sapsuckers fed upon only occasionally, and generally lightly, were American basswood (*Tilia americana* L.), balsam poplar (*Populus balsamifera* var. *balsamifera*), American beech (*Fagus grandifolia* Ehrh.), and eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch). Most of that feeding occurred here in late September and early October (table 1). Local and migrating birds were involved.

American elm (*Ulmus americana* L.) was fed upon lightly in Maine. It does not appear to be a preferred species if birch and maple are available and producing sap. If not, heavy feeding may occur on elm for short periods, especially late in summer. It also has served as a convenience species near some nests in May and June, generally when red maples were not available.

Elm (*Ulmus* spp.) and silver maple (*Acer saccharinum* L.) were damaged heavily by sapsuckers 18 August, 1965 and earlier, near Kentville, Nova Scotia. Severe damage had occurred on 10 elms and 6 maples, ranging from 3 inches to 14 inches

d.b.h. All were shade trees planted around a large motel. The manager's deep concern about the damage was well justified.

Many berries of red-berried elder (*Sambucus pubens* Michx.) were fed to young sapsuckers by their mother on 6 July, 1964. No evidence of sap or bark feeding on this shrub species was seen.

Speckled alders (*Alnus rugosa* (DuRoi) Spreng.) with heavy sap flow held the interest of an entire family of sapsuckers on 13 July, 1964. Other stems of this species were found earlier and later where sapsuckers had fed heavily, but the birds were not seen feeding. Some alders were killed. Most of the feeding appeared to occur about mid-summer. Alder has been an important food species at some locations in Maine where trees higher on the preference list were not available.

In Maine, most of the feeding on apple (*Malus* spp.) trees apparently occurred after late summer. Local birds used it when birch sap was not available in sufficient quantities. The limited evidence I have for Maine indicated very heavy feeding on apple trees by fall migrants, and limited use by local birds at other seasons.

The damage would be much more severe on apple trees if the sap holes were as large as those made during summer feeding on other hardwoods. Small gimlet-type holes normally are found here. Some larger sap holes were made by local juvenile birds in August 1968.

If sapsuckers visit an area, one of the easiest places to see the damage is in an old apple orchard, or near wooded margins in producing orchards.

Tree Sizes Damaged

Most of the trees damaged had an average d.b.h. of 4 to 8 inches. However, the range of diameters observed varied from a minimum of 2 inches to a maximum of 16 inches.

SOME MANAGEMENT IMPLICATIONS

In other regions.—Sapsuckers cannot be dismissed lightly because the tree species damaged here do not exist, or are of minor importance, in other regions. One thing appears quite certain: If sapsuckers spend much time in an area, they probably are feeding on live, woody vegetation of some kind.

The feeding patterns observed here might be similar elsewhere in the northern nesting range—wherever the tree species are similar and nesting occurs. Elsewhere, differences probably occur in the tree species used and the feeding dates—especially in the wintering ranges.

Should damaged trees be cut?—We do not know how sapsuckers would react if their favorite feeding trees were removed for stand improvement. In this region, when sapsuckers kill their own favorite feeding trees, they simply move to other trees and continue their feeding. I have seen that repeatedly. In those areas where timber cutting has removed sapsucker-damaged trees, the birds began drilling undamaged trees. In other areas, heavy cutting has forced the birds to concentrate in adjacent woodlands, where abnormally severe sapsucker damage then occurred.

Cutting sapsucker-damaged trees to improve timber stands might be more likely to discourage migrant birds if they had another source of food within reasonable distance. But nesting sapsuckers would still need feeding trees. I believe local sapsuckers would simply turn to the available trees left in the stand—and these might be the best trees left after timber stand improvement.

Healthy trees also damaged.—Prior wounds on a tree are not necessary to attract sapsuckers. If sapsuckers occupy a nesting territory in this region, they will readily start new wounds on undamaged healthy trees. Among the 535 trees used for this study, only 5 had sapsucker drilling above earlier wounds made by an agent other than sapsuckers: 3 were above cankers or conks, 1 was above a partial porcupine girdle, and 1 was above a

dead area that probably resulted from sapsucker drilling about 6 years earlier.

However, old sapsucker wounds on trees are highly attractive to sapsuckers. These wounds provide the basis for much future intensive sapsucker feeding in this region, and I believe the same should apply in any region. These trees may—or may not—be used first. It is common, in stands where there are many trees to choose from, for sapsuckers to begin feeding on undamaged trees, even though old feeding wounds occur on other trees nearby. For example, among a different group of 557 sapsucker-damaged trees I found in 1964, 49 percent had only damage that had been done prior to 1964, 25 percent had old and 1964 damage, and 26 percent had only 1964 damage. There were 116 conifers and 441 hardwoods.

Sapsuckers kill trees.—Can sapsuckers kill trees? That question has been asked often. They are known to kill at least 32 species of trees, shrubs and vines (*4*). For over 50 years persons reporting sapsucker damage have said that sapsuckers can kill trees of some species (*1, 4, 5, 6*). Occasionally it has been hinted that some other virulent organism also may be involved, but evidence has not been presented to support it.

In the course of this study I watched 22 trees gradually die during a period in which they sustained severe sapsucker damage: 16 were paper birch, 1 was gray birch, 1 yellow birch, and 4 red maple. The same birds and trees were observed repeatedly from the time damage began until the trees died. No other kind of animal damage appeared on these trees. When the band of holes became large enough, and occurred below all branches, the entire tree died. If one or more branches—of any size—occurred below the holes, they remained alive, but the tree above the holes was killed. The latter condition is common; it occurred on 112 hardwoods of the 557 sapsucker-damaged trees I found in 1964.

Hemlock a key species.—Hemlocks may be an important link in the life history of sapsuckers. It is an important early spring food in Maine for local and migrating birds. The evidence indicates that the same applies in the Adirondack Mountains of New York, and on the Allegheny National Forest in northern

Pennsylvania. Feeding occurs on eastern hemlock in Vermont and West Virginia, and on Carolina hemlock in South Carolina and Georgia (*4*).

A western race of sapsucker damages western hemlock (*2, 4, 11*).

I believe that future observations will reveal similar use of hemlock over a much larger area. If you wish to make a quick check for evidence of sapsuckers, look at the hemlocks. If nesting does not occur in a region, migrants probably made the holes.

Apple a key species.—Sapsucker damage can be found in many apple orchards. But the impact of that damage on fruit trees has not been studied intensively in the Northeast (*4*). Current evidence suggests that trees of the apple family may form an important link in the life history of sapsuckers. These trees provide an abundant, easily located source of food during fall migration—and may thus sustain the birds on their movement to their wintering grounds among southern forests.

Migrants add to damage.—Migrating sapsuckers add to the damage caused by local nesting birds. Both spring and fall migrants normally used the same trees damaged earlier the same year, or in preceding years. Migrants pass through our local sapsucker territories in several waves. Individual migrants stay and feed for several hours to a week or longer. Later migrants may use the same trees.

I believe this habit also might prevail farther south, between the summer and winter ranges. But there only waves of migrants would be involved, not nesting or wintering birds..

Conclusion

The species of trees used by sapsuckers in the forests of northern New England have been determined, together with some information about frequency of use. Other research is providing a means for surveying sapsucker populations and identifying sapsucker family territories. These studies increase our knowledge of the habitat requirements and ecology of the

bird and should lead to development of feasible methods for surveying and predicting sapsucker impact on timber management and other forest uses.

Literature Cited

(1) Adams, Charles C.
1923. NOTES ON THE RELATION OF BIRDS TO ADIRONDACK FOREST VEGETATION. Roosevelt Wild Life Bull. 1:487-519.

(2) Howell, Thomas R.
1952. NATURAL HISTORY AND DIFFERENTIATION IN THE YELLOW-BELLIED SAPSUCKER. Condor 54: 237-282.

(3) Jorgensen, Richard N., and Sophie L. Lecznar.
1964. ANATOMY OF HEMLOCK RING SHAKE ASSOCIATED WITH SAPSUCKER INJURY. U. S. Forest Serv. Res. Paper NE-21, 9 pp. N.E. Forest Exp. Sta., Upper Darby, Pa.

(4) McAtee, W. L.
1911. WOODPECKERS IN RELATION TO TREES AND WOOD PRODUCTS. U. S. Dep. Agr. Biol. Survey Bull. 39, 99 pp.

(5) McAtee, W. L.
1962. THE RELATION OF BIRDS TO WOODLOTS IN NEW YORK STATE. Roosevelt Wild Life Bull. 4:7-152.

(6) Northeastern Forest Experiment Station.
1965. REPORT 1964. U. S. Forest Serv. N.E. Forest Exp. Sta., 77 pp.

(7) Northeastern Forest Experiment Station.
1967. REPORT 1966. U. S. Forest Serv. N.E. Forest Exp. Sta., 98 pp.

(8) Ohman, John H., and K. J. Kessler, Jr.
1964. BLACK BARK AS AN INDICATOR OF BIRD PECK DEFECT IN SUGAR MAPLE. U. S. Forest Serv. Res. Paper LS-14, 8 pp. Lake States Forest Exp. Sta., St. Paul, Minn.

(9) Shigo, Alex L.
1963. RING SHAKE ASSOCIATED WITH SAPSUCKER INJURY. U. S. Forest Serv. Res. Paper NE-8, 10 pp. N.E. Forest Exp. Sta., Upper Darby, Pa.

(10) Todd, W. E. Clyde.
1940. BIRDS OF WESTERN PENNSYLVANIA. Univ. Pittsburgh Press, 710 pp.

(11) Ziller, Wolf G., and David Stirling.
1961. SAPSUCKER DAMAGE IN COASTAL BRITISH COLUMBIA. Forestry Chron. 37: 331-335.

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An Approach to YELLOW - POPLAR Tree Valuation

by Edwin L. Lucas

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An Approach to YELLOW-POPLAR Tree Valuation

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INTRODUCTION

HARDWOOD log grades are used today to classify logs or trees with similar characteristics into groups with stated average percentages of grade lumber so that an average value may be determined for the group. This discontinuous grading system introduces a *grouping error* in estimating value because there is really no distinct difference in value between the poorest logs of one grade and the best logs of the next lower grade. This grouping error could be eliminated by using a *continuous* grading system—a continuous predictor.

This paper describes the technique used to develop, and explore the feasibility of, a continuous predictor for the grade lumber yield of standing yellow-poplar trees (*Liriodendron tulipifera L.*).[1]

[1] Two previously-developed yellow-poplar grading systems (*5*) each have three grades of trees, and hence the grouping error is built into them. The equations listed later in this paper still contain the grouping error, because current log grade yield tables were used to compute lumber recoveries by grade. When actual sawed yields are used to establish the equation coefficients, however, the grouping error will be eliminated.

Our results show that a continuous predictor for the lumber recovery of standing yellow-poplar trees is feasible. Equations were developed that, when applied to a sample of 126 yellow-poplar trees in Illinois, Kentucky, and Ohio, predicted a value of lumber yield within 2 percent of the value computed from individual log yields based on Forest Service log grades (*6*).

An important feature of the equations is that they require only three tree characteristics to be measured: diameter breast height, merchantable height, and the number of 5-foot clear cuttings on the four faces of the 16-foot butt log. Thus the equations require only one characteristic to be measured in addition to those now needed for volume estimation, and they eliminate the need for further grading in the field. Another feature is that the calculated yields are divided into each of the seven yellow-poplar standard lumber grades (*3*).

SAMPLE DATA

The data used came from yellow-poplar tree diagrams originally collected as part of an overall study developed at the Carbondale, Illinois, field office of the Central States Forest Experiment Station to establish hardwood tree grades. The data sheets for 226 yellow-poplar trees collected during the Carbondale tree-grade study were used in developing the prediction equations reported in this paper. Merchantable tree heights ranged from 13 to 96 feet, and d.b.h. from 12 to 36 inches.

PROCEDURES

Variables

Seven dependent variables were used. The value for each was expressed in terms of the board-foot volume of 4/4 green lumber recoverable from the tree in each of the seven standard yellow-poplar grades (*3*): FAS, Selects, Saps, No. 1 Common, No. 2A Common, No. 2B Common, and No. 3 Common.

The board-foot yield for each log in the tree was calculated by multiplying the International 1/4-inch log rule gross scale by

the appropriate percent lumber grade yield.[2] The volume in each lumber grade was summed over all logs in the tree to arrive at total tree lumber volume.

Two sources of error are apparent in computing tree lumber yields in this manner. They are the variances associated with the lumber grade yield tables, and the log-scale rule (International 1/4-inch log rule) used in computing gross log volume. As there is no practical method for evaluating these two sources of error, the computed lumber yields were accepted as an estimate of the actual yield.

Twenty-four independent variables (15 tree characteristics and 9 transformations) were examined (table 1). Except for merchantable tree height, only those characteristics occurring in the first 16 feet in the tree above a 12-inch stump were evaluated. Space limitations preclude a detailed description of the independent variables. Those that were significant in the predictions will be described later.

Developing the Model

The data were analyzed by using the least-squares principle for fitting a multiple linear[3] regression model. The regression models used were of the general form:

$$Y_i = B_0 + B_1 X_{1i} + B_2 X_{2i} - - - + B_k X_{ki} + e_i$$

Where:

n = Number of sample units.

K = Number of independent variables.

Y_i = Observed value of the dependent variable for the i^{th} unit in the sample, i = 1,2, - - -, n.

X_{ji} = The value of the j^{th} independent variable on the i^{th} sample unit, j = 1,2, - - -, k.

B_j = The regression coefficient of the j^{th} independent variable.

---

[2]The percent lumber yields for the logs grade 1 through 3 were taken from the Forest Products Laboratory's curved percent yield tables. Yields for logs that did not meet the requirements for grade 3 logs, but were merchantable under the standards set for this study, were taken from tables developed by Campbell (*2*).

[3]Linear refers to the linearity of the model's coefficients and not to the independent variables.

However, to get a reliable estimate of the confidence interval and its associated probability, the specific terms in the model, and their form, must be selected before the analysis is started. Not enough was known about the relationship between the dependent and independent variables to construct such a model. To overcome this, the initial sample of 226 trees was divided into two parts. One hundred tree diagrams were randomly selected and used to derive the models. These models were then used with the remaining sample data to develop the final prediction equations.

The data for all 31 variables, 7 dependent and 24 independent, were compiled; and a simple correlation matrix was computed. Using the correlation matrix as a guide, we selected 10 sets of independent variables for model searching (table 1).

A step-wise fitting procedure was used to select those independent variables within each set that had a significant effect on the dependent variable. For example, in set 1 there were six independent variables: X_1, X_2, X_{20}, X_{21}, X_{22}, and X_{23}; the step-wise procedure was used to fit

$$
\begin{aligned}
&X_1, X_2, X_{20}, X_{21}, X_{22}, X_{23} \text{ on } Y_1\\
&X_1, X_2, X_{20}, X_{21}, X_{22}, X_{23} \text{ on } Y_2\\
&\text{-} \qquad\qquad\qquad\

Table 1.—Independent variables and the selected sets used for model searching

Symbol	Independent variable	Set number									
		1	2	3	4	5	6	7	8	9	10
X1	Diameter breast height (DBH)	x[a]	x	x	x	x	x	x	x	x	x
X2	Tree merchantable height (HT)	x	x	x	x	x	x	x	x	x	x
X3	2-foot cuttings, BPK[b] a defect	—	—	—	—	—	—	—	—	—	—
X4	3-foot cuttings, BPK a defect	—	—	—	—	—	—	—	—	x	—
X5	5-foot cuttings, BPK a defect	—	—	—	—	—	—	—	—	—	x
X6	Select quarter sections, BPK a defect	—	—	—	—	x	—	—	—	—	—
X7	Select 4-foot sections, BPK a defect	—	—	x	—	x	—	—	—	—	—
X8	Total defect count, BPK a defect	—	—	x	—	—	—	—	x	—	—
X9	Total defect count, BPK no defect	—	—	—	x	—	x	—	—	—	—
X10	Total knot count	—	—	x	x	x	x	x	—	x	x
X11	2-foot cuttings, BPK no defect	—	—	—	—	—	—	—	—	—	—
X12	3-foot cuttings, BPK no defect	—	—	—	—	—	—	—	—	—	—
X13	5-foot cuttings, BPK no defect	—	—	—	—	—	—	—	—	—	—
X14	Select quarter sections, BPK no defect	—	—	—	—	—	—	x	—	—	—
X15	Select 4-foot sections, BPK no defect	—	—	—	x	—	—	—	—	—	—
X16	X_1 squared	—	—	x	x	—	—	—	—	—	—
X17	X_{11} squared	—	x	—	—	—	—	—	—	—	—
X18	X_{12} squared	—	x	—	—	—	—	—	—	—	—
X19	X_{13} squared	—	x	—	—	—	—	—	—	—	—
X20	X_3 squared	x	—	—	—	—	—	—	—	—	—
X21	X_4 squared	x	—	—	—	—	—	—	—	x	—
X22	X_5 squared	x	—	—	—	—	—	—	—	—	x
X23	DBH^2 times HT	x	x	x	x	x	x	x	x	x	x
X24	1/DBH times HT	—	—	—	—	—	—	—	—	—	—

[a]X indicates the variable was selected for the set; i.e., set one contains the independent variables X_1, X_2, X_{20}, X_{21}, X_{22}, and X_{23}.

[b]BPK indicates birdpeck.

Table 2.—Board-foot volume and lumber value by grade for the 100 sample trees

Lumber grade	Symbol	Price per M board feet	Lumber volume		Lumber value	
		Dollars	*Board-feet*	*Percent*	*Dollars*	*Percent*
FAS	Y_1	220	1,291	2.7	284	4.7
Selects	Y_2	210	437	.9	92	1.5
Saps	Y_3	200	1,528	3.2	306	5.1
1C	Y_4	160	17,952	37.0	2,872	48.0
2A	Y_5	107	14,182	29.2	1,517	25.4
2B	Y_6	73	8,505	17.5	621	10.4
3C	Y_7	63	4,597	9.5	290	4.9
Total	–	–	48,492	100.0	5,982	100.0

use in fitting the final prediction equations with the remaining sample data. An average R^2 for each set did not seem advisable because of the large differential between the yields of the seven grades of lumber and their respective prices (table 2). To account for differences in lumber grade prices and yields, a weighted R^2 value was used to evaluate the predictive properties of individual sets.

Three terms were used in calculating the weighted R^2: (1) a price relative for each grade, calculated by dividing the price per M board feet for each grade by the price of No. 1 Common lumber; (2) a volume relative for each grade, determined by dividing the total volume in each lumber grade by the volume in the Select grade; and (3) the coefficient of determination, R^2, for each grade. The cross-product of the three terms was calculated for each lumber grade and then was summed for all grades by sets. The assumption of the weighting scheme was that the set with the highest sum would be the best overall predictor of tree value.

In set 10, knot count was significant only in predicting the No. 2B Common grade of lumber (table 3). It was deleted from the set, and the step-wise analysis was rerun for the No. 2B

Table 3.—Variables that were significant in predicting lumber grade yields, and the associated equation coefficients of determination (R^2)

Independent variable	Independent variables found to be significant in predicting the dependent variables						
	Y_1 FAS	Y_2 Sel	Y_3 Saps	Y_4 1C	Y_5 2A	Y_6 2B	Y_7 3C
				SET 1			
X_1	x[a]	x	—	—	—	—	x
X_2	—	—	—	x	—	x	x
X_{20}	—	—	—	—	—	—	—
X_{21}	x	x	x	x	—	—	x
X_{22}	—	—	—	—	x	x	—
X_{23}	—	—	x	x	x	x	x
R^2	0.47	0.48	0.51	0.89	0.79	0.45	0.62
				SET 9			
X_1	—	—	—	—	—	—	x
X_2	x	x	—	x	—	x	x
X_4	—	—	—	x	—	—	—
X_{10}	—	—	—	—	—	x	—
X_{21}	x	x	x	—	x	x	x
X_{23}	—	—	x	x	x	x	x
R^2	0.47	0.48	0.51	0.89	0.78	0.46	0.62
				SET 10			
X_1	x	x	—	—	—	—	x
X_2	—	—	—	x	x	x	x
X_5	x	x	—	x	x	x	—
X_{10}	—	—	—	—	—	x	—
X_{22}	—	—	x	—	—	—	x
X_{23}	—	—	x	x	x	x	x
R^2	0.46	0.47	0.52	0.89	0.79	0.48	0.61

[a]Indicates the variable was significant at the 0.05 probability level.

equation. There was only a slight reduction (0.48 to 0.46) in the R^2 value when knot count was omitted. Knot count was thus dropped from set 10 and the weighted R^2 was recalculated.

The results of the weighted R^2 calculation for each set were as follows:

Set	*Weighted R^2*
1	40.56
9	40.55
10	40.53
5	40.39

Set	*Weighted* R^2
3	40.29
6	39.83
4	39.30
2	39.26
8	38.84
7	37.82

The weighted R^2s were interpreted as showing no practical differences in the predictive properties of the three top-ranking sets: 1, 9, and 10. These sets were the only ones considered for further investigation.

Since knot count had been dropped from set 10 without an appreciable reduction in R^2, it was assumed that the same could be done in set 9. This left sets 9 and 10 with three variables requiring field measurements, and set 1 with four. Set 1 was eliminated because it had a greater number of variables requiring measurements. Set 10 was selected for developing the prediction equations because, in field application, it would be the least expensive to use. The equations were developed for this set, using the remaining 126 trees from the initial sample.

Prediction Equations

In set 10, five variables (excluding knot count) were significant in predicting at least one of the seven dependent variables. Each of the seven prediction equations contains all five of these variables. Using the independent variables in set 10 and the remaining 126 sample trees, the following prediction equations were developed:

$$Y_{FAS} = 116.7101 - 5.6021\,X_1 - 1.8947\,X_2 - 0.3431\,X_5 + 0.1987\,X_{22} + 0.004478\,X_{23}$$

$$Y_{SEL} = 25.5130 - 1.2318\,X_1 - 0.4754\,X_2 + 0.1487\,X_5 + 0.05897\,X_{22} + 0.001116\,X_{23}$$

$$Y_{Saps} = -46.4927 + 2.0630\,X_1 + 0.2903\,X_2 + 2.4959\,X_5 + 0.03040\,X_{22} - 0.0003053\,X_{23}$$

$$Y_{1C} = 213.9343 - 9.3608\,X_1 - 5.9098\,X_2 + 2.6055\,X_5 + 0.4121\,X_{22} + 0.01898\,X_{23}$$

$$Y_{2A} = -112.1970 + 6.8718\,X_1 + 1.4716\,X_2 - 3.2297\,X_5 + 0.06368\,X_{22} + 0.002520\,X_{23}$$

$$Y_{2B} = -39.0000 + 2.5340\,X_1 + 1.3392\,X_2 - 1.5769\,X_5 - 0.01917\,X_{22} + 0.0008661\,X_{23}$$

$$Y_{3C} = -31.8421 + 1.9420\,X_1 + 1.5599\,X_2 - 2.1895\,X_5 + 0.06318\,X_{22} - 0.0008192\,X_{23}$$

Where:

X_1 = D.b.h. rounded to the nearest inch.

X_2 = Tree merchantable height, rounded to the nearest foot.

X_5 = The number of 5-foot clear cuttings. Clear cuttings are defined as the portions of the face that lie between defects (*4*), or between log ends and defects. The value recorded was the total number of 5-foot clear cuttings on all four faces of the indicator section.

X_{22} = The X_5 count squared.

X_{23} = D.b.h. squared times merchantable height.

The actual volume of the 126 sample trees was 65 M board feet. The predicted volume of these trees was 63 M board feet, a difference of only 3 percent. When the value of the recoverable lumber from the trees was considered, the difference between actual and predicted value was only 2 percent (table 4).

Table 4.—Comparison of actual and equation-predicted lumber volume and values for 126 yellow-poplar trees

Lumber grade	Price per M board feet	Actual volume	Predicted volume	Actual value	Predicted value
	Dollars	*Board feet*	*Board feet*	*Dollars*	*Dollars*
FAS	220	2,159	2,227	474.98	489.94
Sel	210	709	1,135	148.89	238.35
Saps	200	2,208	2,312	441.60	462.40
1C	160	25,383	25,161	4,061.28	4,025.76
2A	107	17,875	15,627	1,912.62	1,672.09
2B	73	10,513	10,674	767.45	779.20
3C	63	6,299	6,208	396.84	391.10
Total		65,146	63,344	8,203.66	8,058.84
Difference		–	- 1,802	–	-144.82
Percent difference		–	2.77	–	1.76

SUMMARY AND CONCLUSIONS

Advantages of the System

The tree-valuation system reported has several advantages over valuation systems based on discrete tree grades.

First, it is less expensive to use. Of the three variables requiring field measurement, two—d.b.h. and merchantable height—are measured anyway when estimating tree volume. By measuring one additional variable—the number of 5-foot clear cuttings—the user can get lumber volume by grade, and this can be converted easily to dollar value. Since volume estimation is a necessary requisite for timber appraisal, the added cost of field application would be small. The forester can examine the indicator section of the selected trees and record the values for the independent variables on field punch cards. With the prediction equations, the data could then be processed directly by computers.

Second, the predictions are given directly in board-foot volume by lumber grade and can easily be converted to current gross dollar value. Since the predictions are given directly in board-feet, volume tables are not necessary; the equations have their own built-in volume tables. As with any statistical procedure of this nature, the equations may not show the value of an individual tree accurately; they should be used to estimate the total value of a number of trees.

The statistics for making an evaluation of the precision of the estimate are readily available (tables 5 and 6). The user not only knows what the estimated lumber recovery is, but also the variation he might expect in his estimate.

Research Implications

The feasibility of a continuous predictor of tree value has been demonstrated. The design of the study insures, for statistical purposes, the applicability of the equations to field use. However, the use of the equations is limited by the restrictions imposed on their development. The lumber recovery volumes by grade were calculated volumes and are subject to

Table 5.—The relevant statistics and the associated confidence intervals for the seven lumber-grade predictions, using the set 10 independent variables

Dependent variables		R^2	$S_{Y\cdot\cdot}$	S_Y[a]	Y	Confidence interval[a] for study sample			
						0.05 probability level		0.01 probability level	
Symbol	*Grade*		*Board feet*	*Board feet*	*Board feet*	*Board feet*	*%*	*Board feet*	*%*
Y_1	FAS	0.74	18.43	1.64	17.1	3.3	19.0	4.3	25.1
Y_2	Sel	.74	5.22	.46	5.6	.9	16.4	1.2	21.6
Y_3	Saps	.43	14.59	1.30	17.5	2.6	14.7	3.4	19.4
Y_4	1C	.93	51.95	4.63	201.4	9.2	4.6	12.1	6.0
Y_5	2A	.82	34.94	3.11	141.9	6.2	4.3	8.1	5.7
Y_6	2B	.66	24.98	2.23	83.4	4.4	5.3	5.8	7.0
Y_7	3C	.65	11.02	.98	50.0	1.9	3.9	2.6	5.1

[a]At the mean value of all independent variables. n=126

Table 6.—Mean and inverse matrix of independent variables for use with prediction equations developed from set 10

Independent variables	Mean	Independent variables				
		X_1	X_2	X_5	X_{22}	X_{23}
X_1	21.9	2.310×10^{-3}				
X_2	42.0	4.604×10^{-4}	2.044×10^{-4}			
X_5	4.8	-2.167×10^{-4}	5.111×10^{-5}	5.787×10^{-3}		
X_{22}	34.7	1.696×10^{-5}	-5.897×10^{-6}	4.796×10^{-4}	4.569×10^{-5}	
X_{23}	21822	-8.600×10^{-7}	-2.495×10^{-7}	2.195×10^{-8}	2.146×10^{-10}	4.156×10^{-10}

the errors associated with the log scale and yield tables used. Also, the sample was not selected over the entire range of yellow-poplar, but was taken from commercial logging operations in Illinois, Kentucky, and Ohio. Priority in future work should be given to testing the equations over the geographic range of the species against actual sawed volumes.

The prediction equations are based on an examination of the butt 16-foot log. No other indicator section was tested. By the same decision rules, other indicator section lengths should be tested to see if the lumber recovery estimates are improved. Bulgrin and Schroeder (*1,5*) tried various lengths of indicator sections in the butt 16-foot log and found that the grade of the best 10-foot section was the best predictor of tree quality.

In determining net tree volume, each predicted lumber grade yield must be reduced by the percent of scalable defect contained in the tree. Under the assumption that most scalable defect comes from the core of the log or tree and represents mostly lower grade lumber, errors arise when the yield in each lumber grade is reduced by the same percent of scalable defect. This can result in underestimating the yields of higher grades of lumber and overestimating the yields of the lower grades. In future studies, a variable expressing cull deduction should be added to the equations and tested for significance.

This method gives a continuous predictor of tree value based on lumber as the end product. Future research will be needed to develop methods for valuation of trees for other products—veneer for example—and for multiproduct tree valuation.

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LITERATURE CITED

1. Bulgrin, Erwin H., and Walters, Russell S.
   1959. BUTT-LOG TREE GRADING WORKS IN OHIO. U. S. Forest Serv. Cent. States Forest Exp. Sta. Sta. Note 128, 2 pp. Columbus, Ohio.

2. Campbell, Robert A.
   1959. TREE GRADES GIVE ACCURATE ESTIMATES OF SECOND GROWTH YELLOW POPLAR VALUES. U. S. Forest Serv. SE. Forest Exp. Sta. Sta. Paper 108, 14 pp. Asheville, N. C.

3. National Hardwood Lumber Association.
   1967. RULES FOR THE MEASUREMENT AND INSPECTION OF HARDWOOD LUMBER, 116 pp. Chicago, Ill.

4. Ostrander, M. D., and others.
   1965. A GUIDE TO HARDWOOD LOG GRADING (REVISED). U. S. Forest Serv. NE. Forest Exp. Sta., 50 pp. Upper Darby, Pa.

5. Schroeder, James G.
   1964. A TREE GRADING AND VALUATION SYSTEM FOR YELLOW POPLAR. Forest Prod. J. 14:521-524.

6. United States Forest Products Laboratory.
   1966. HARDWOOD LOG GRADES FOR STANDARD LUMBER. U. S. Forest Serv. Res. Paper FPL 63, 52 pp. Forest Prod. Lab., Madison, Wis.

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